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(54) **SYSTEM AND METHOD FOR
LIQUEFACTION OF NATURAL GAS**

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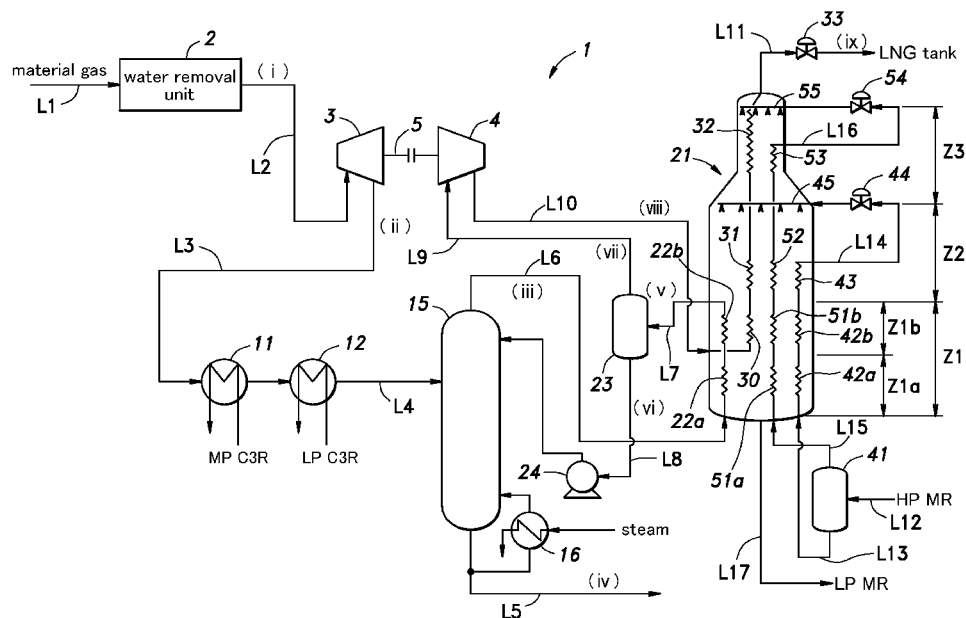
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(57)

ABSTRACT

By using the power generated by an expander by an expansion of material gas, the outlet pressure of a compressor is increased, and a requirement on the cooling capacity of a cooler is reduced. The liquefaction system (1) for natural gas comprises a first expander (3) for generating power by using natural gas under pressure as material gas; a first cooling unit (11, 12) for cooling the material gas depressurized by expansion in the first expander; a distillation unit (15) for reducing or eliminating a heavy component in the material gas by distilling the material gas cooled by the first cooling unit; a first compressor (4) for compressing the material gas from which the heavy component was reduced or eliminated by the distillation unit by using power generated in the first expander; and a liquefaction unit (21) for liquefying the material gas compressed by the first compressor by exchanging heat with a refrigerant.



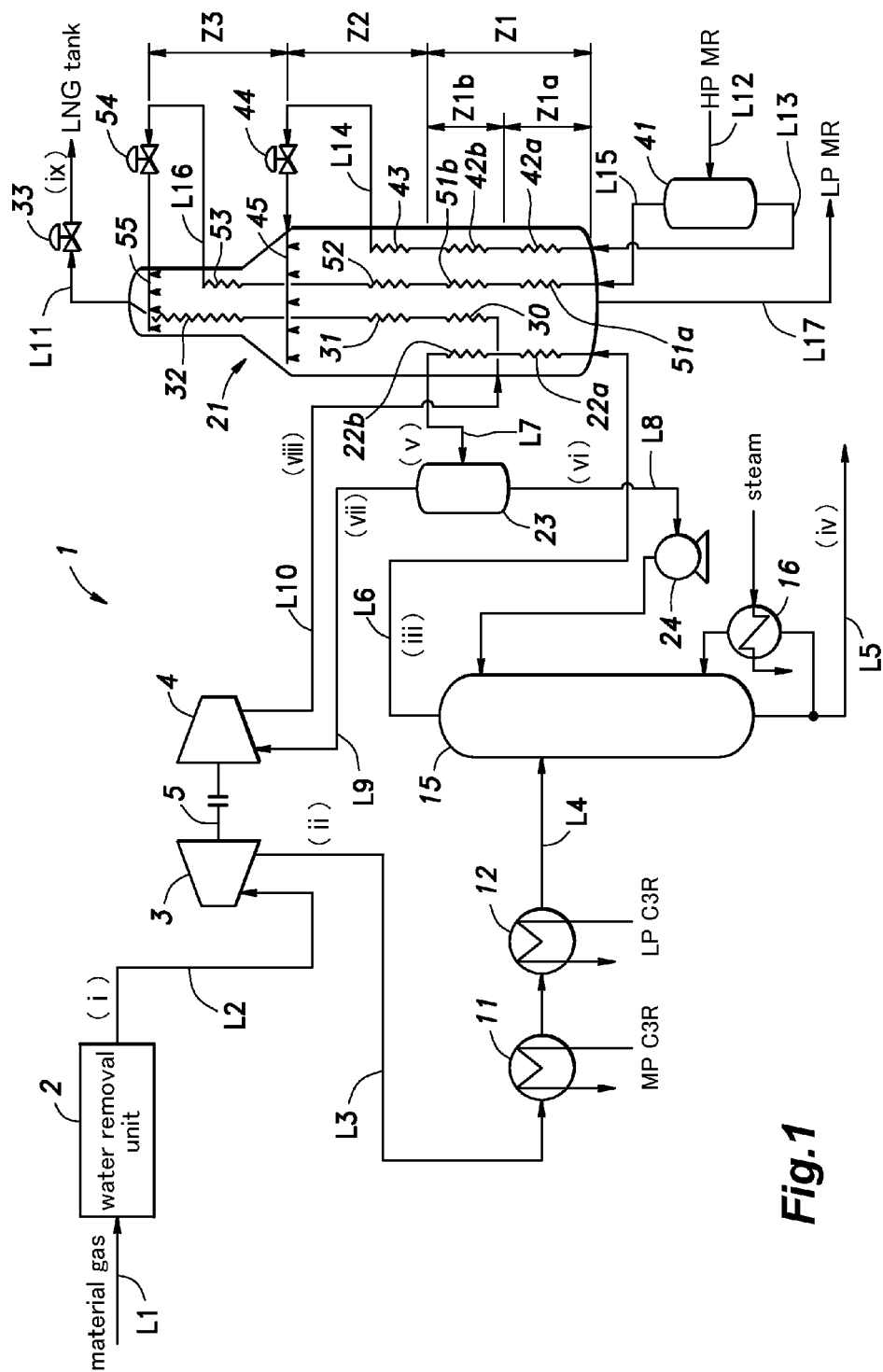
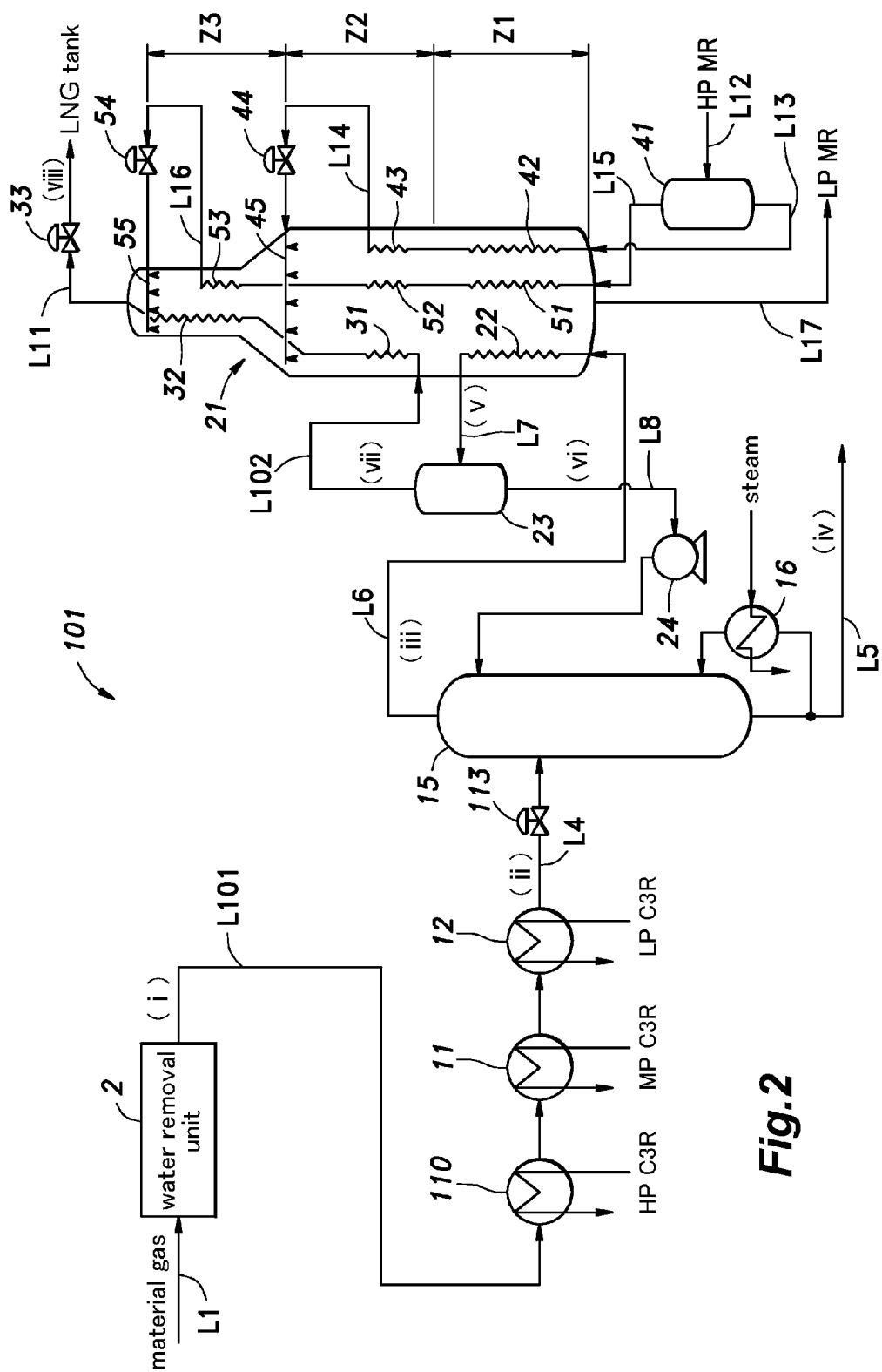


Fig.1



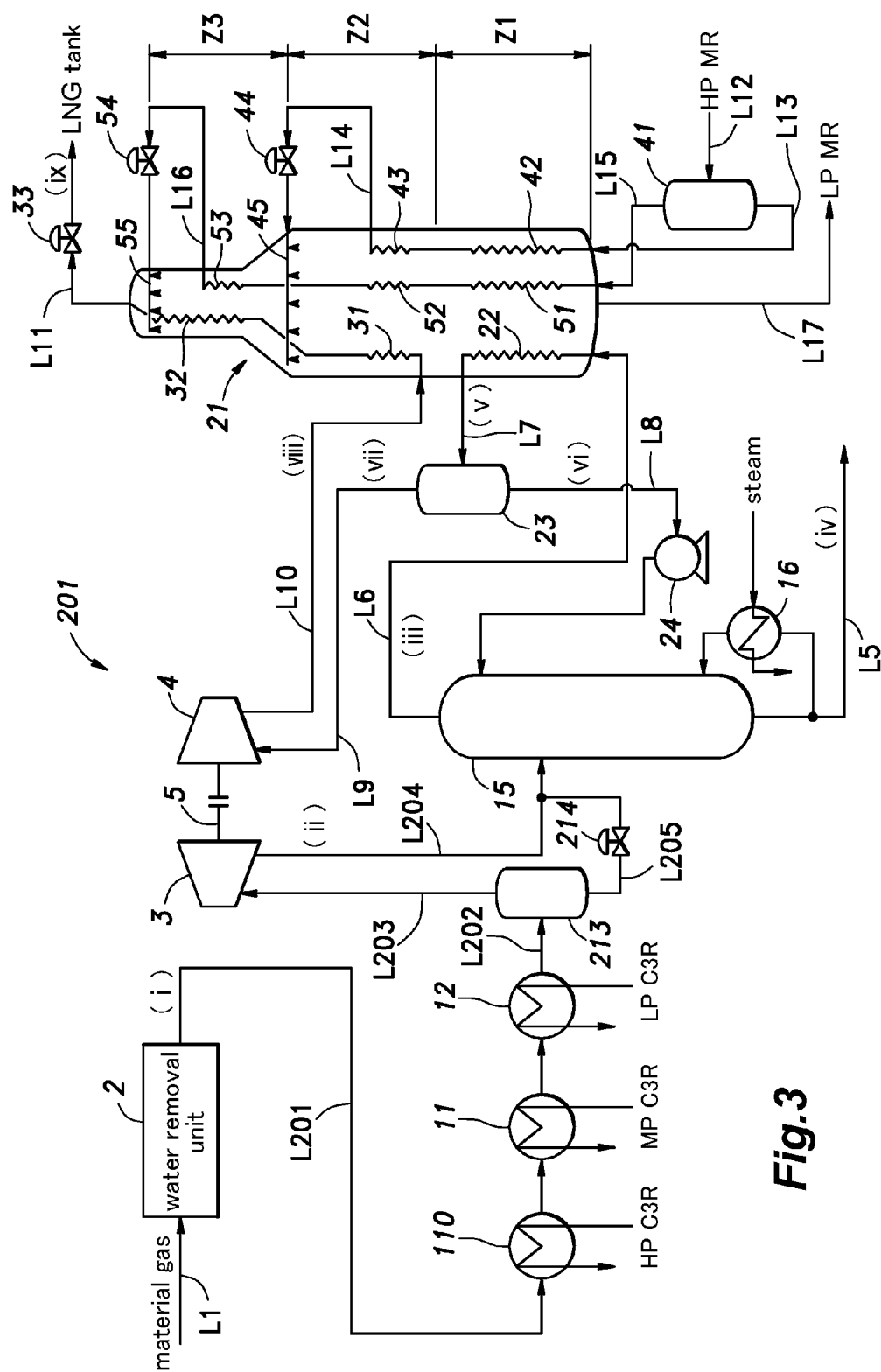


Fig.3

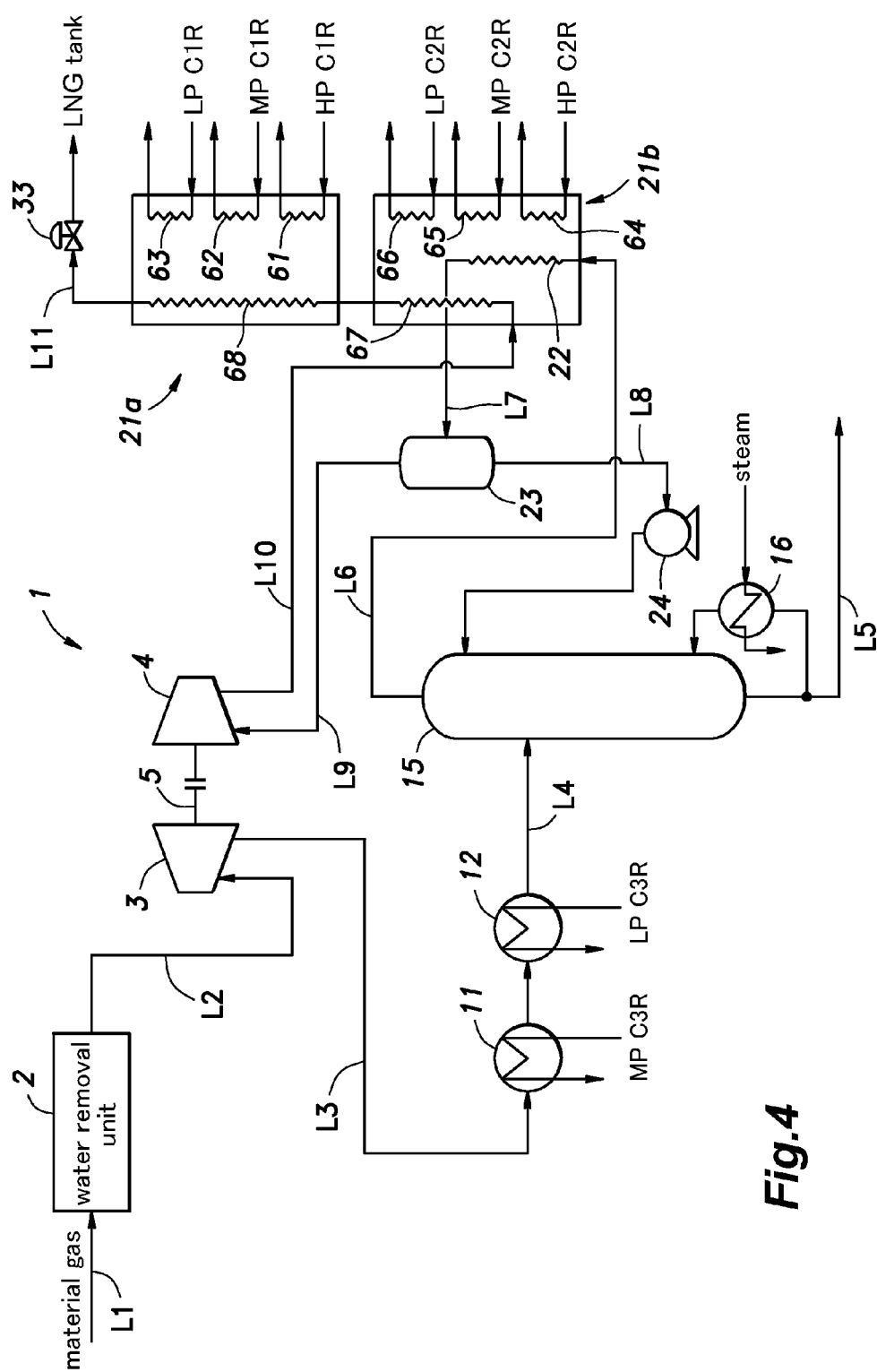
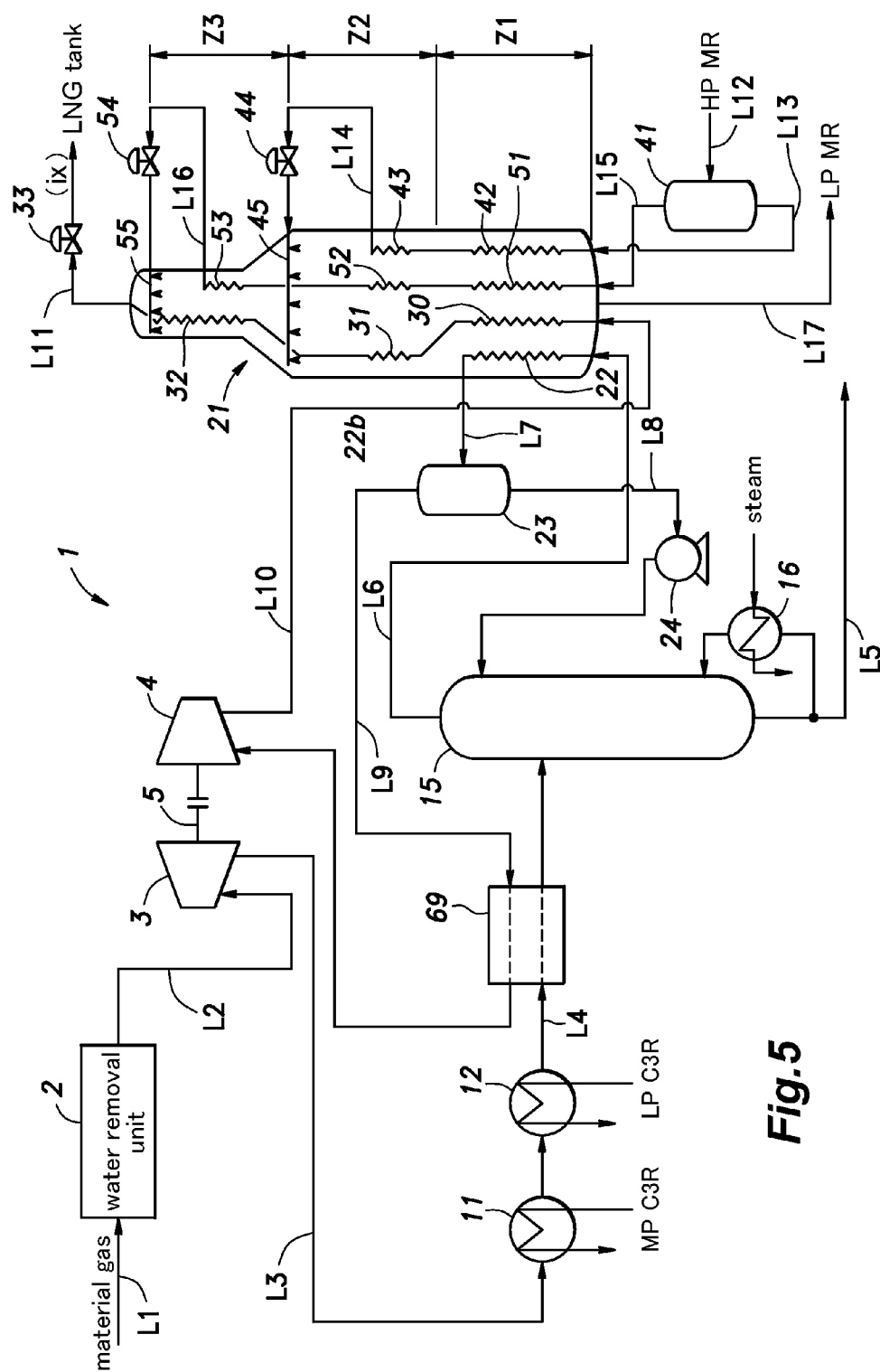


Fig.4



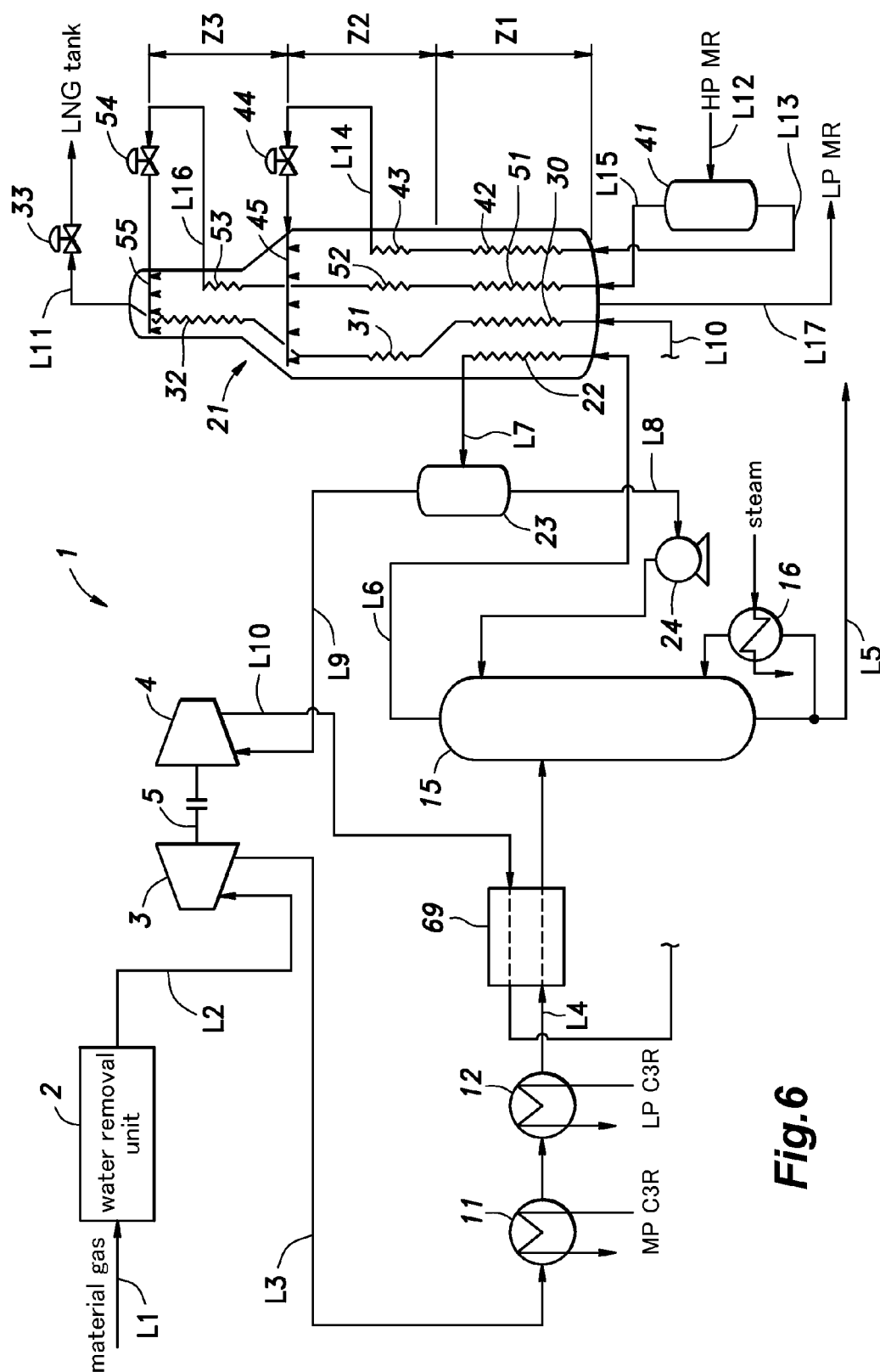


Fig.6

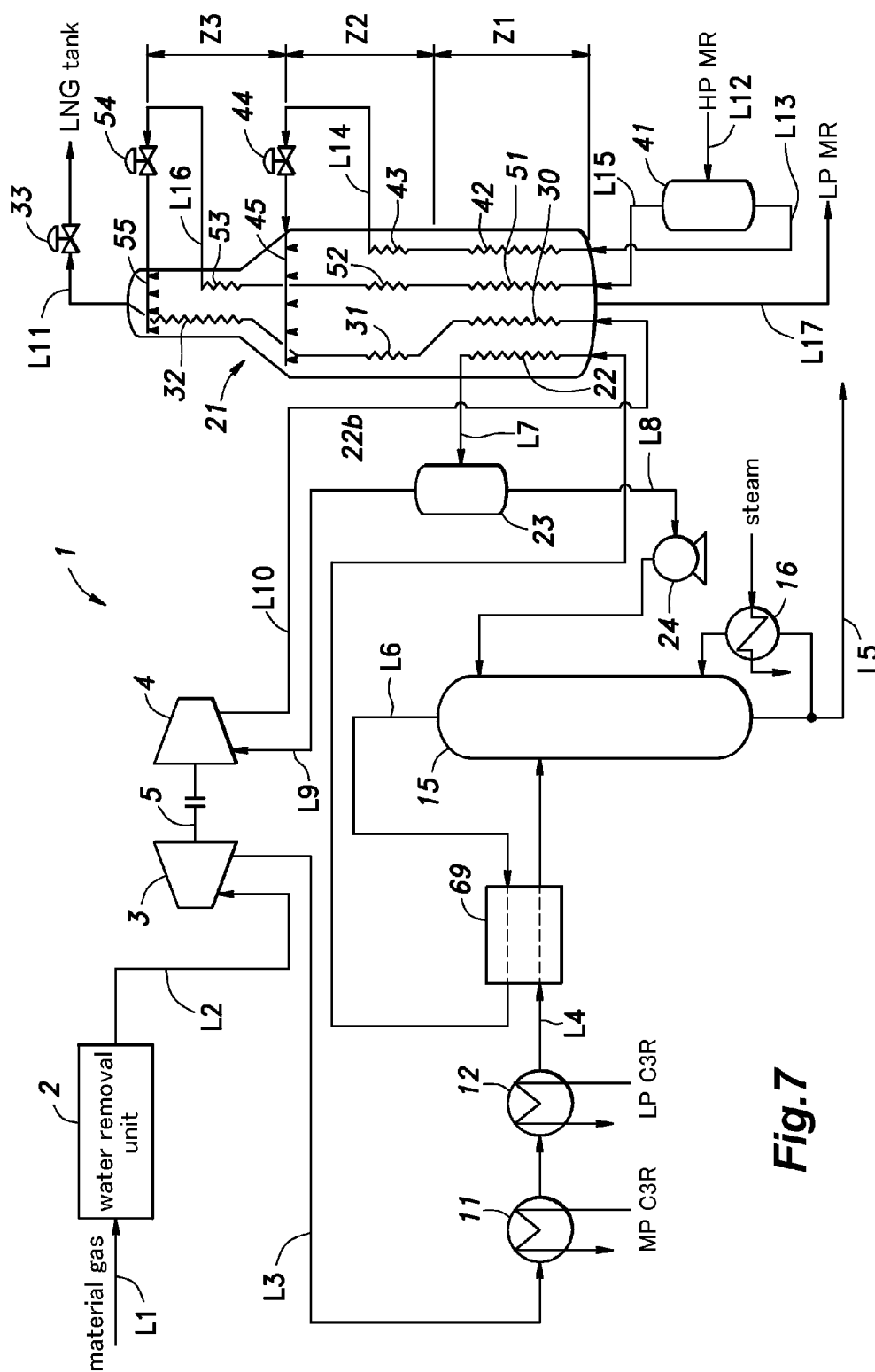


Fig. 7

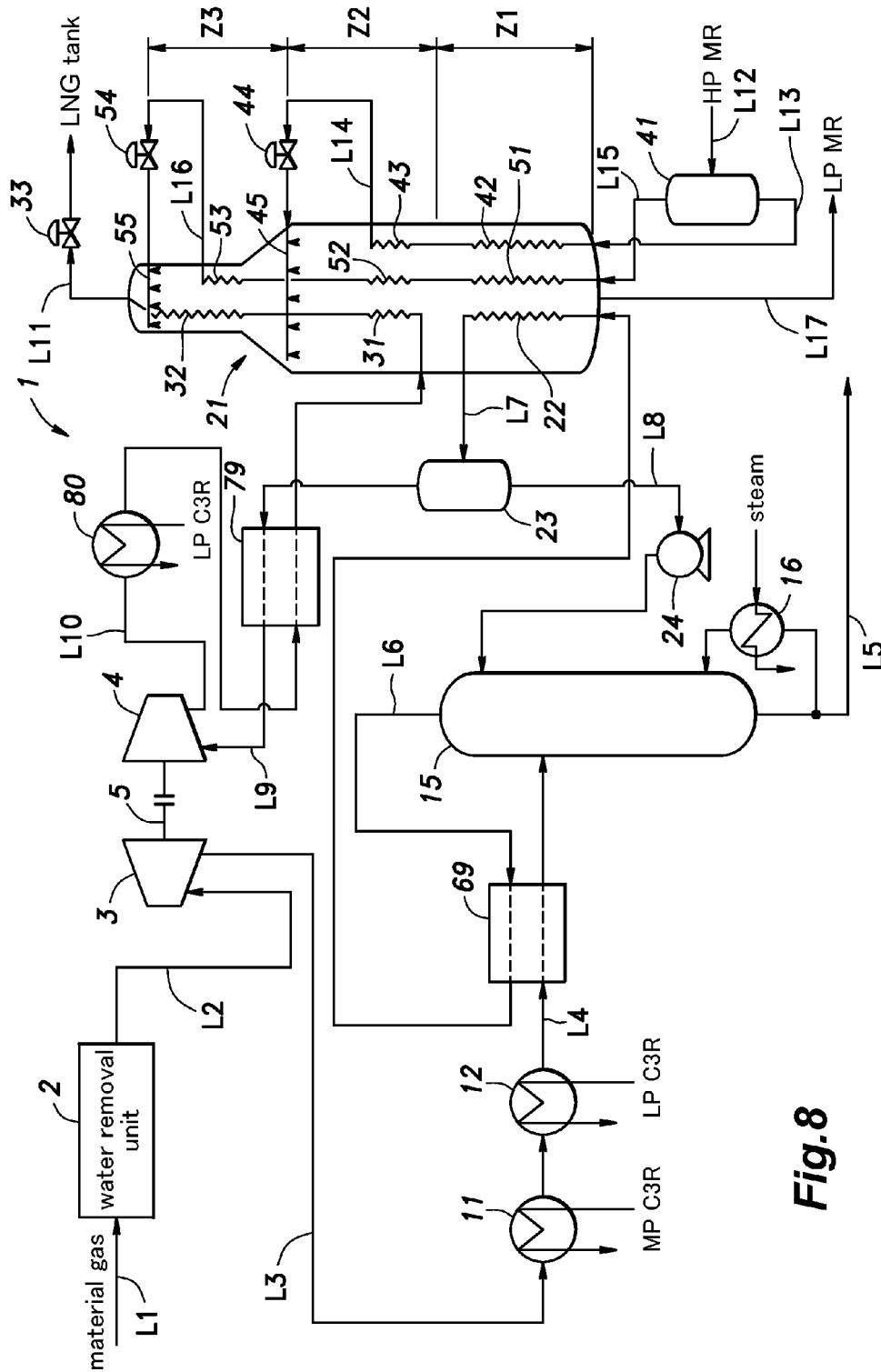


Fig.8

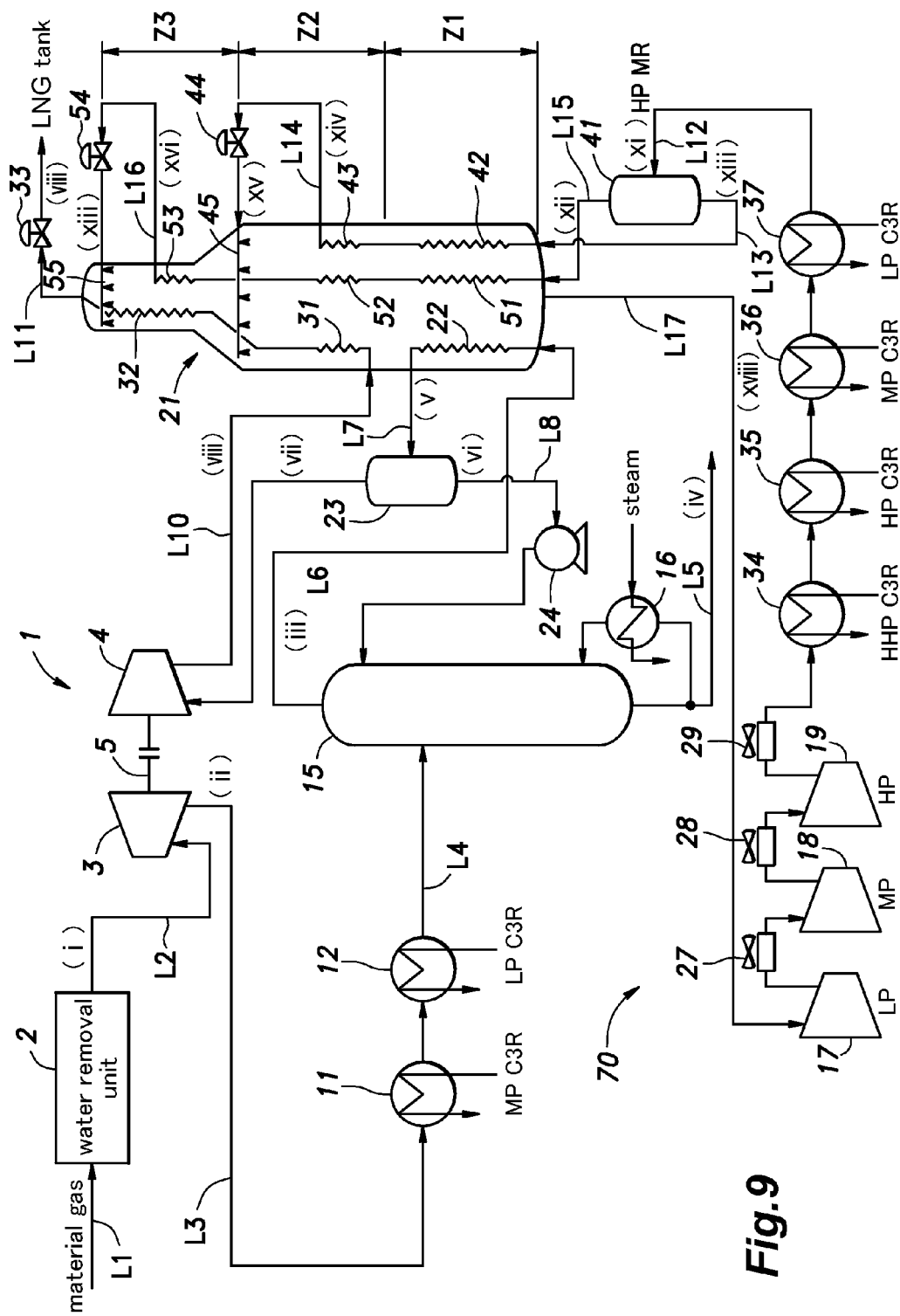


Fig.9

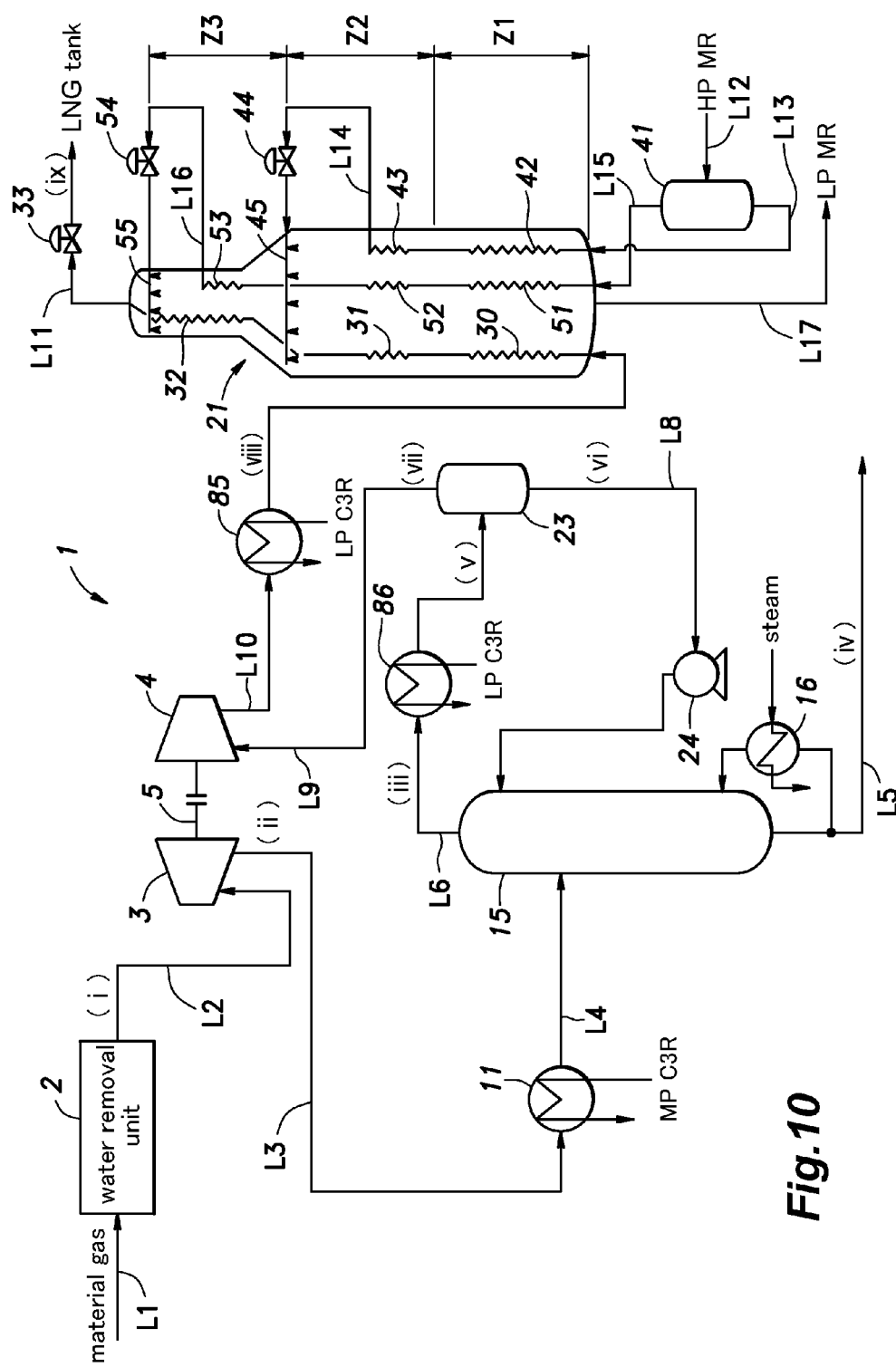
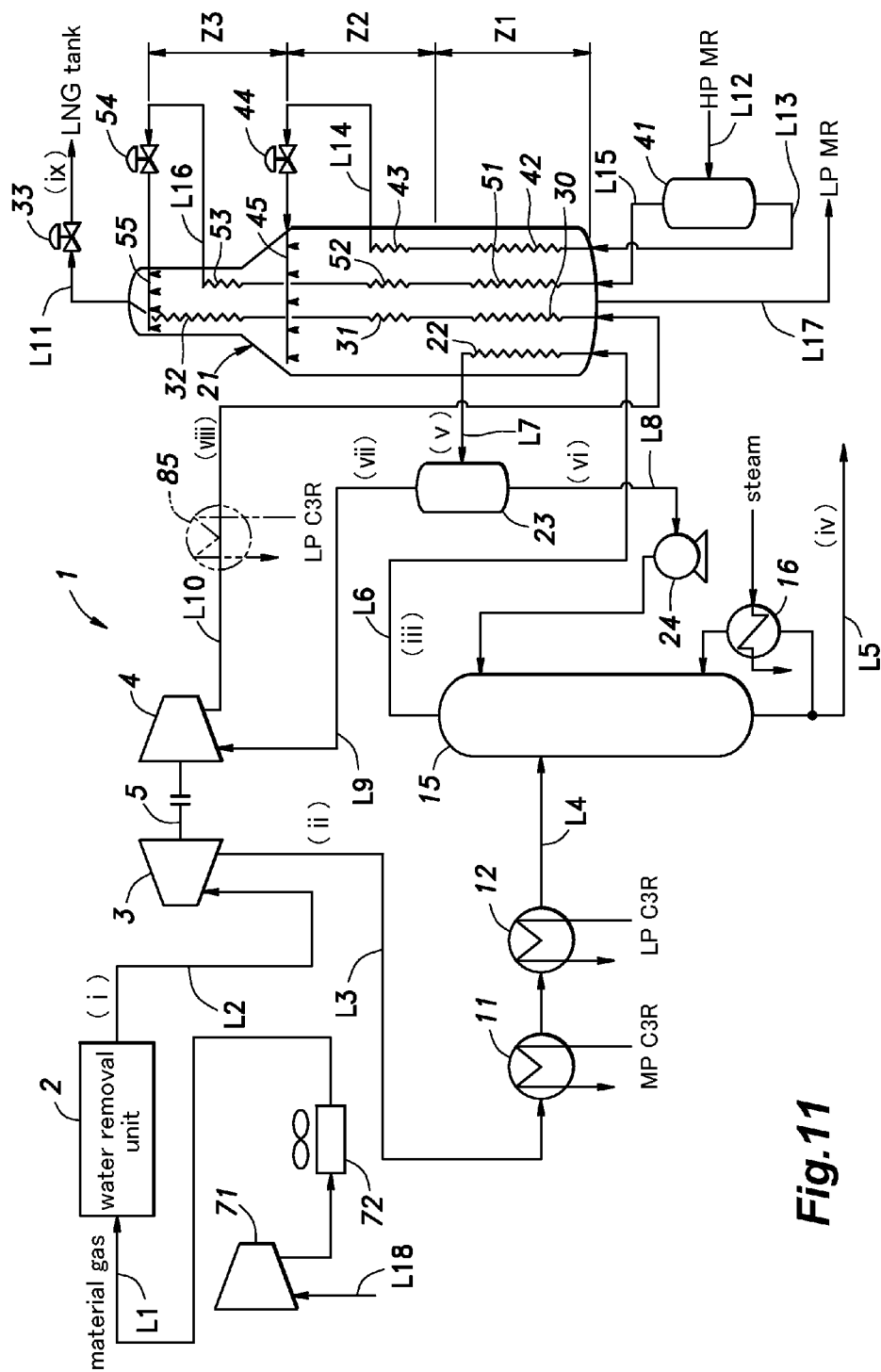
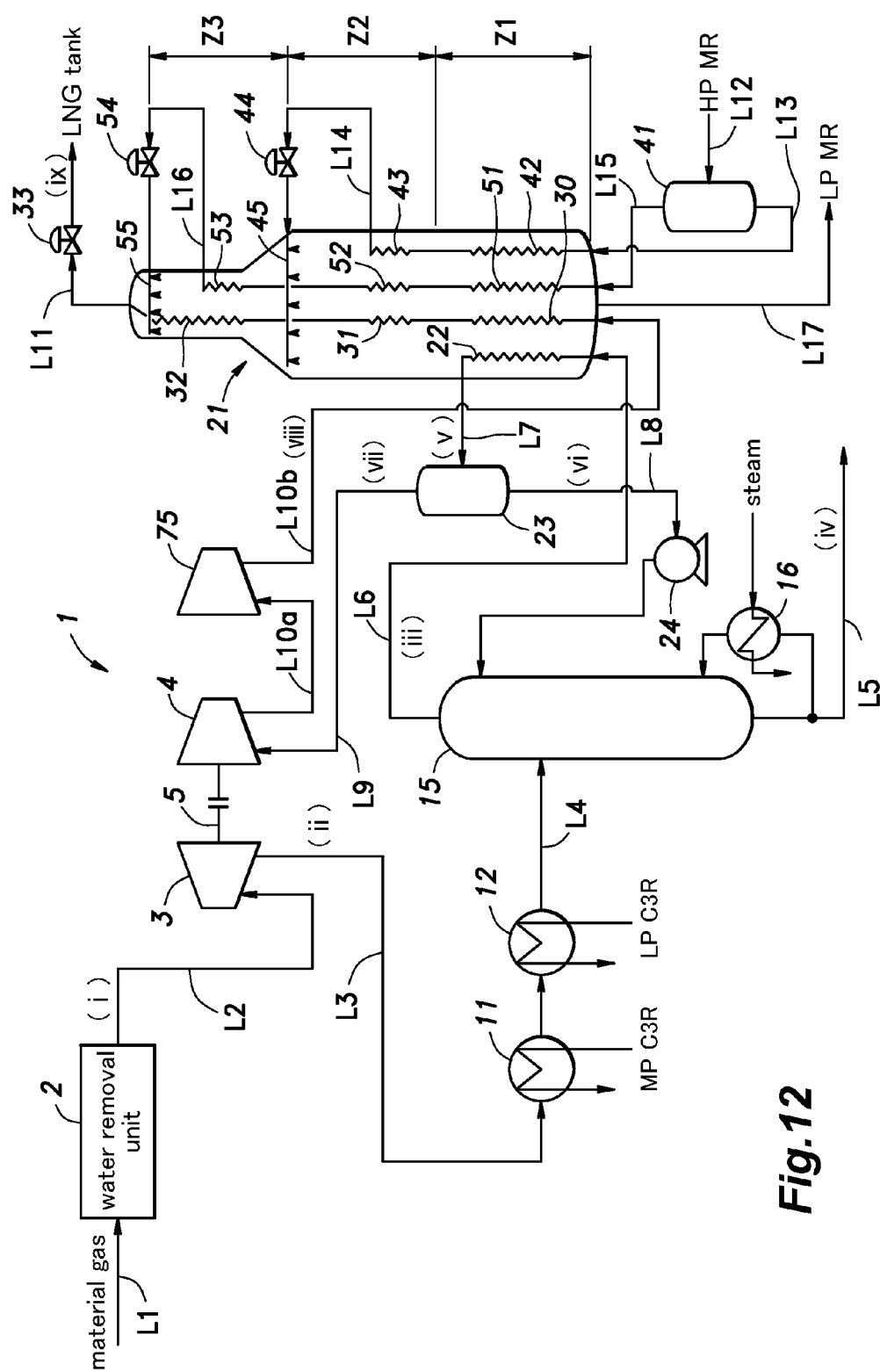
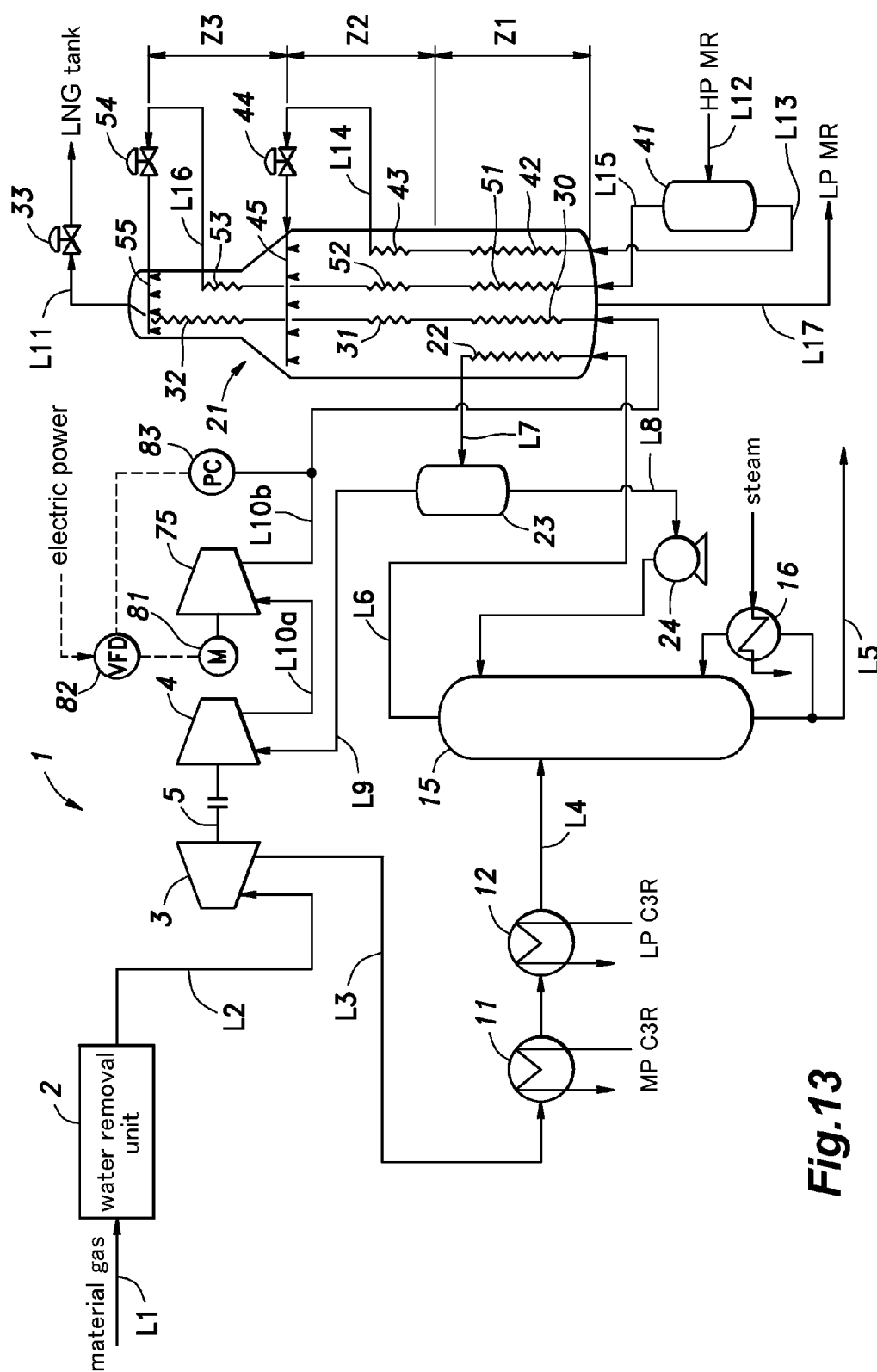


Fig.10







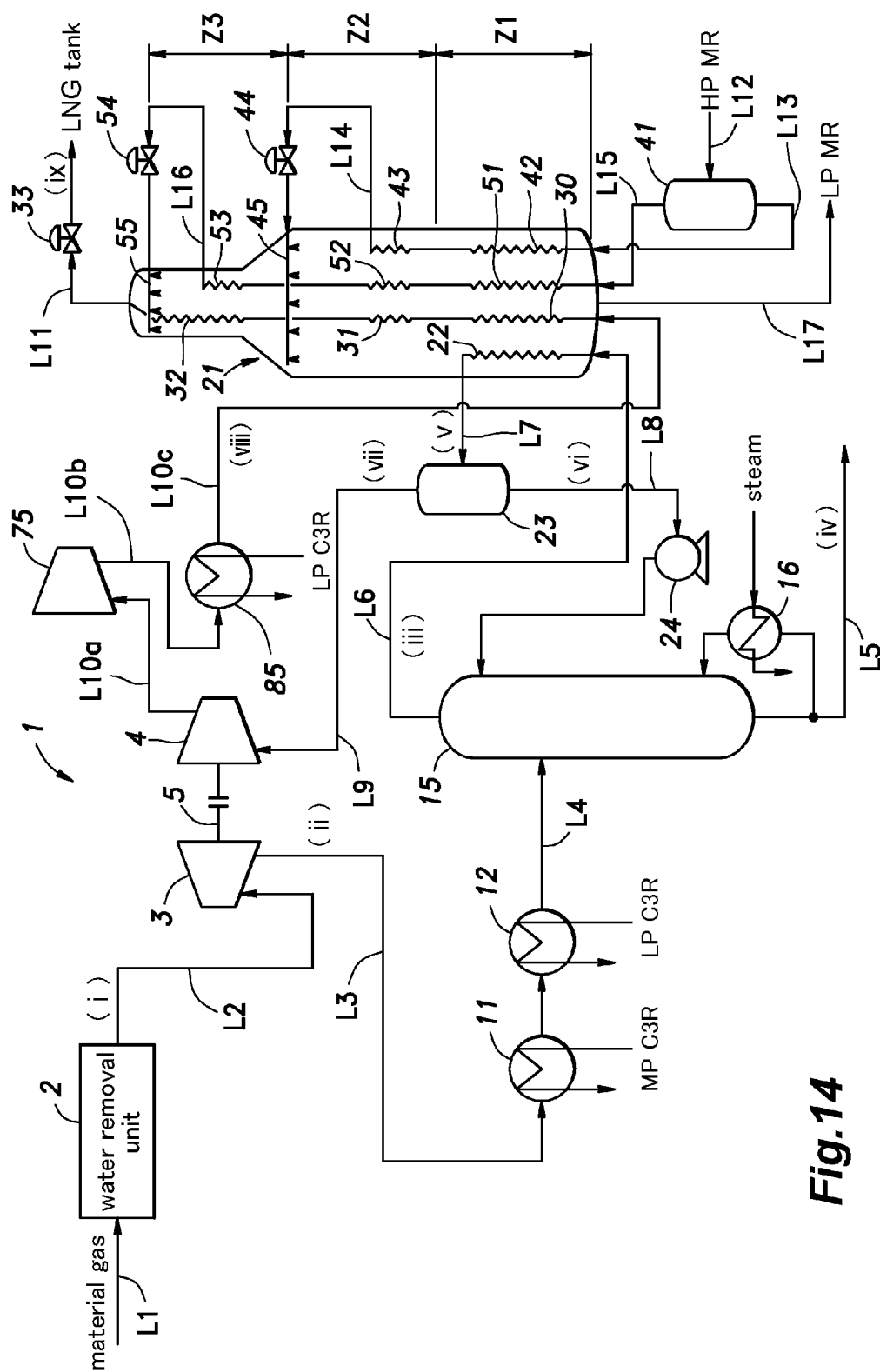


Fig.14



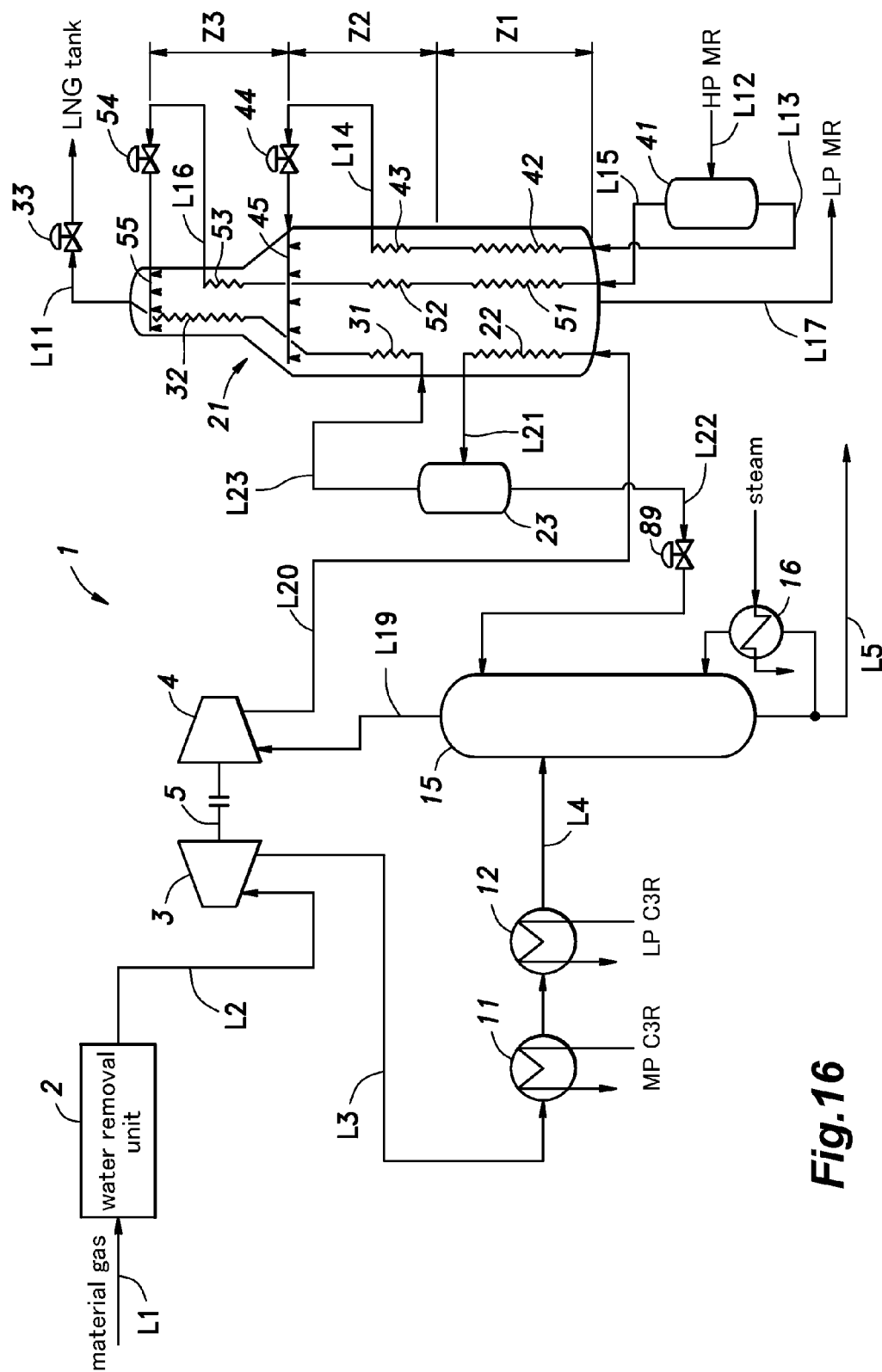
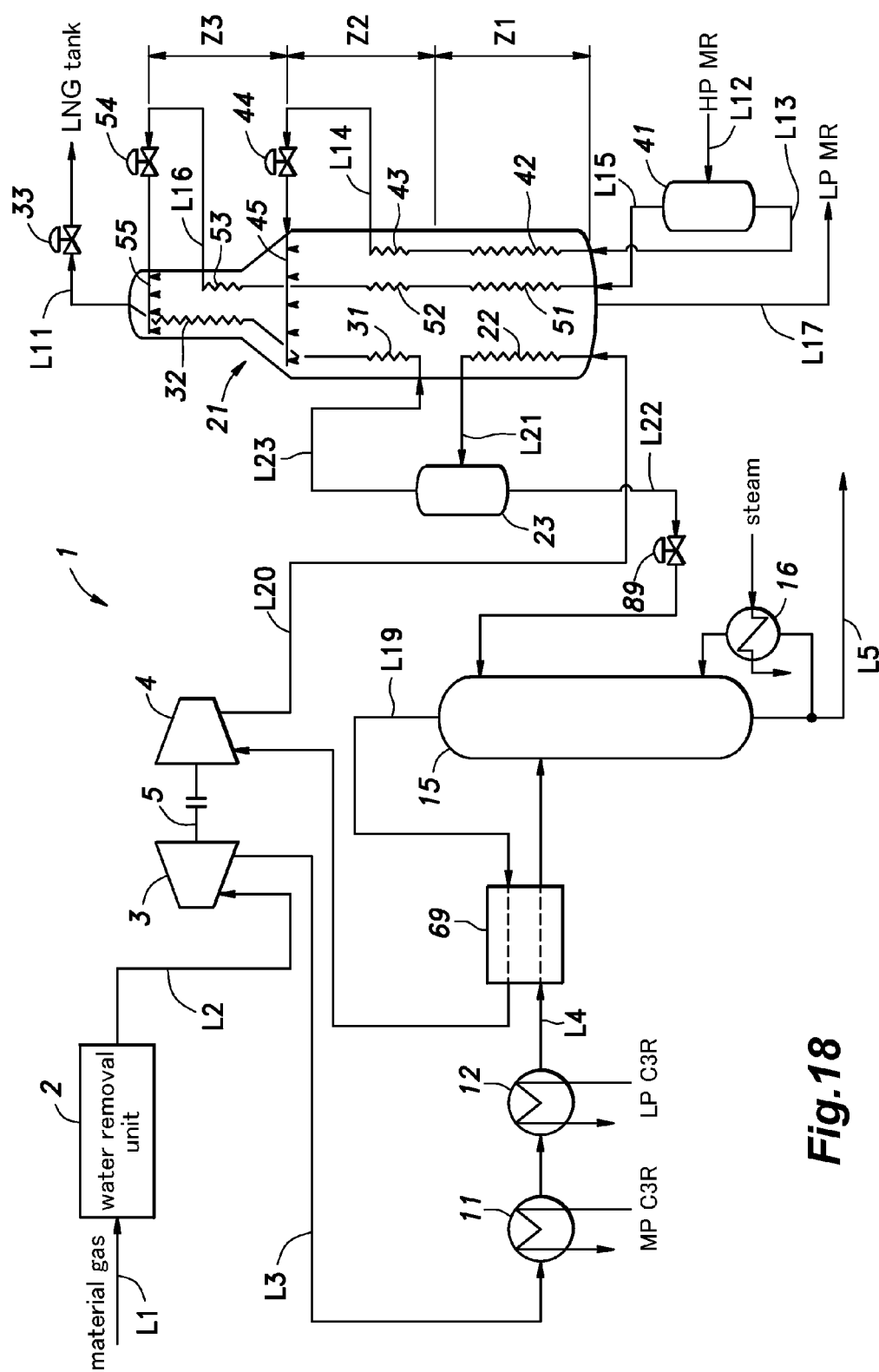


Fig.16



Fig. 17



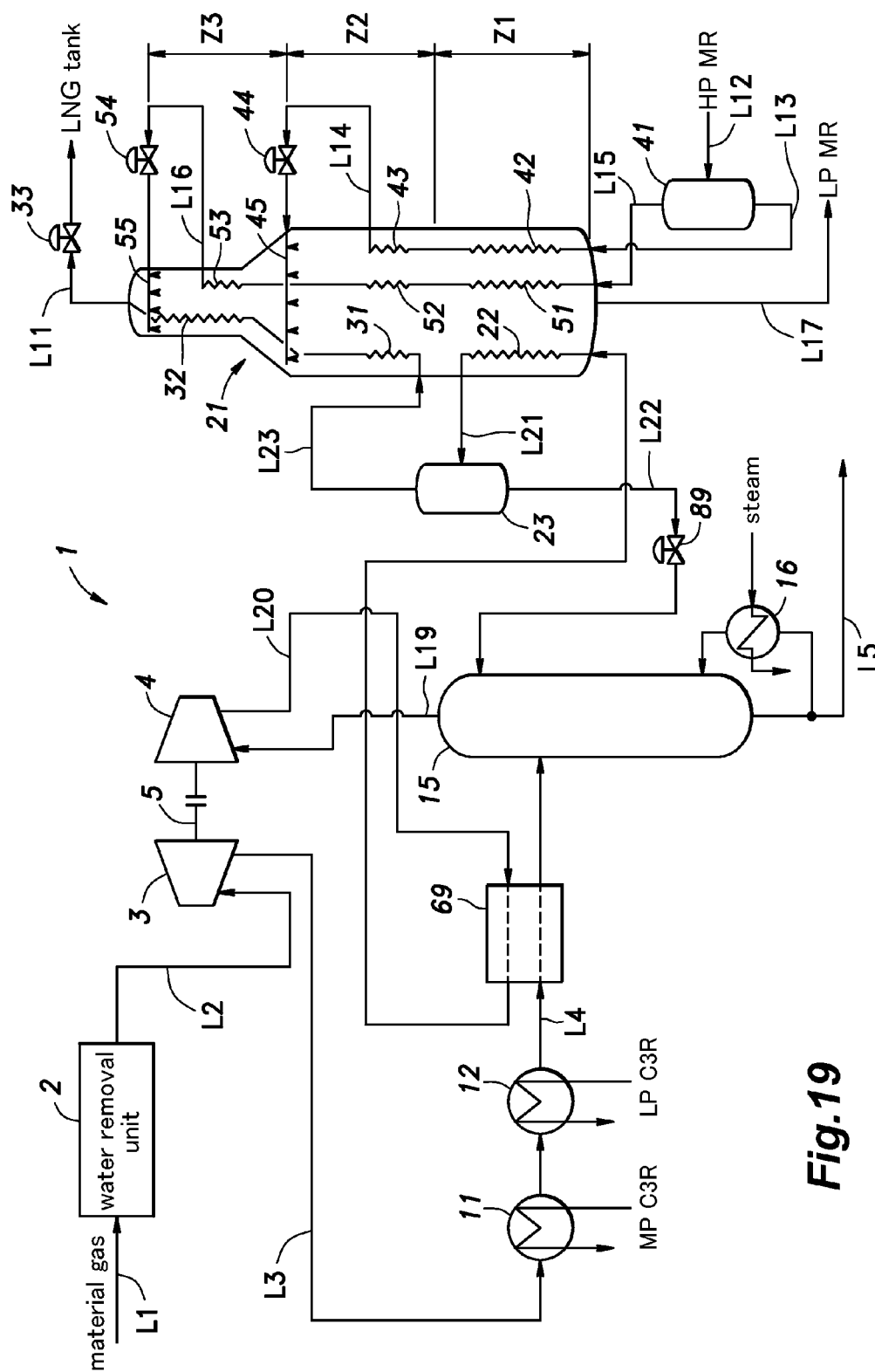
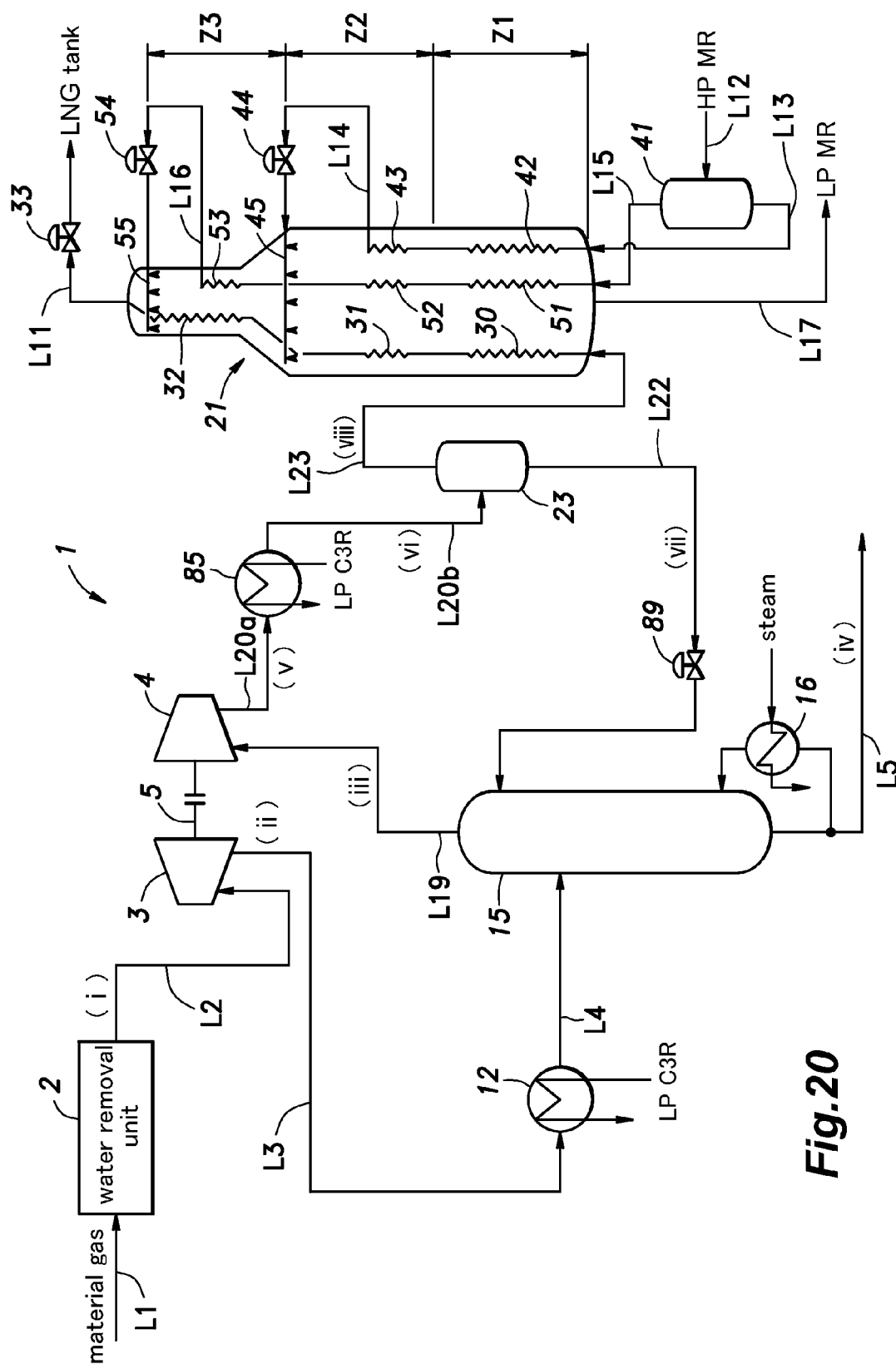
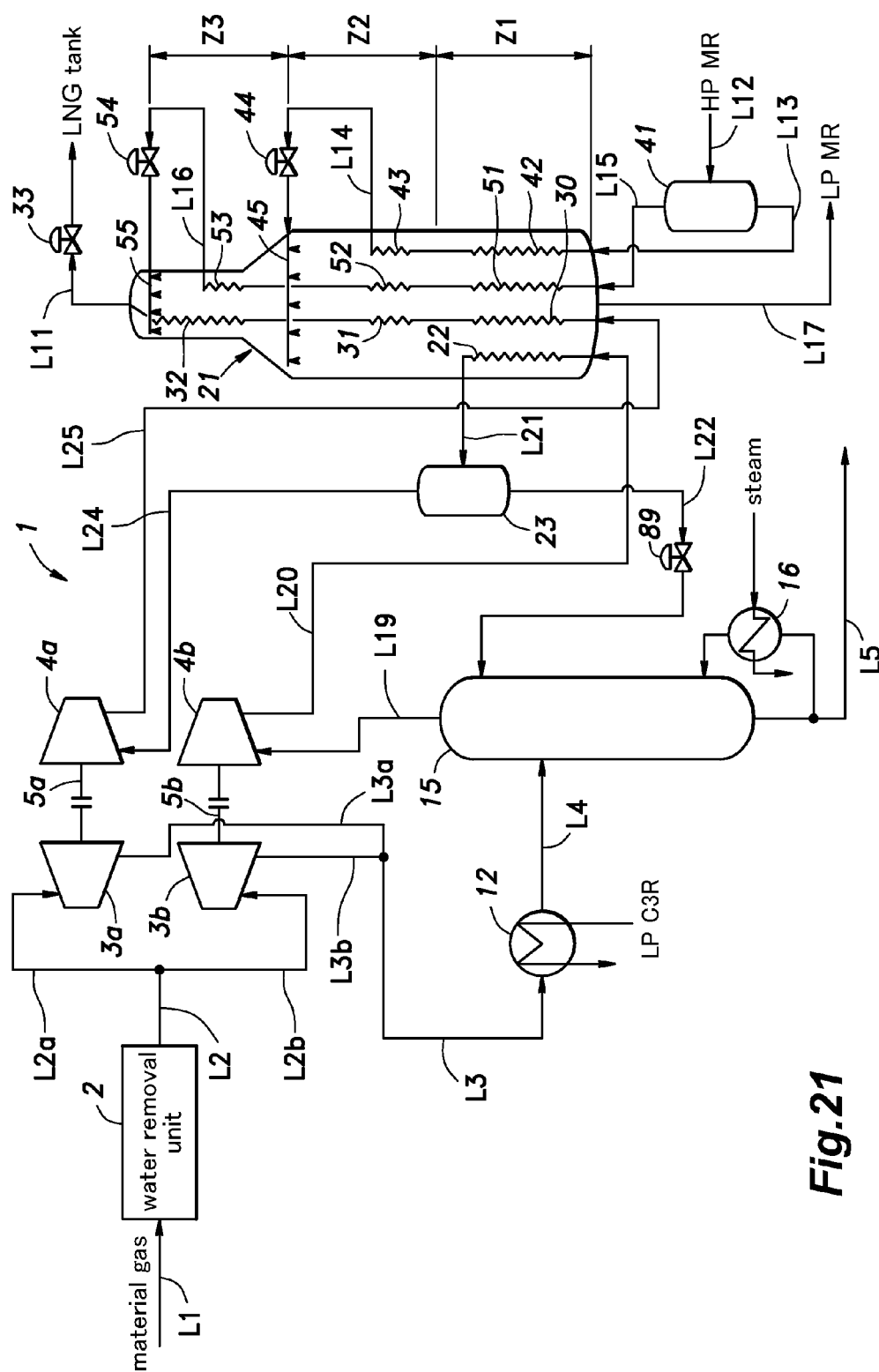


Fig.19





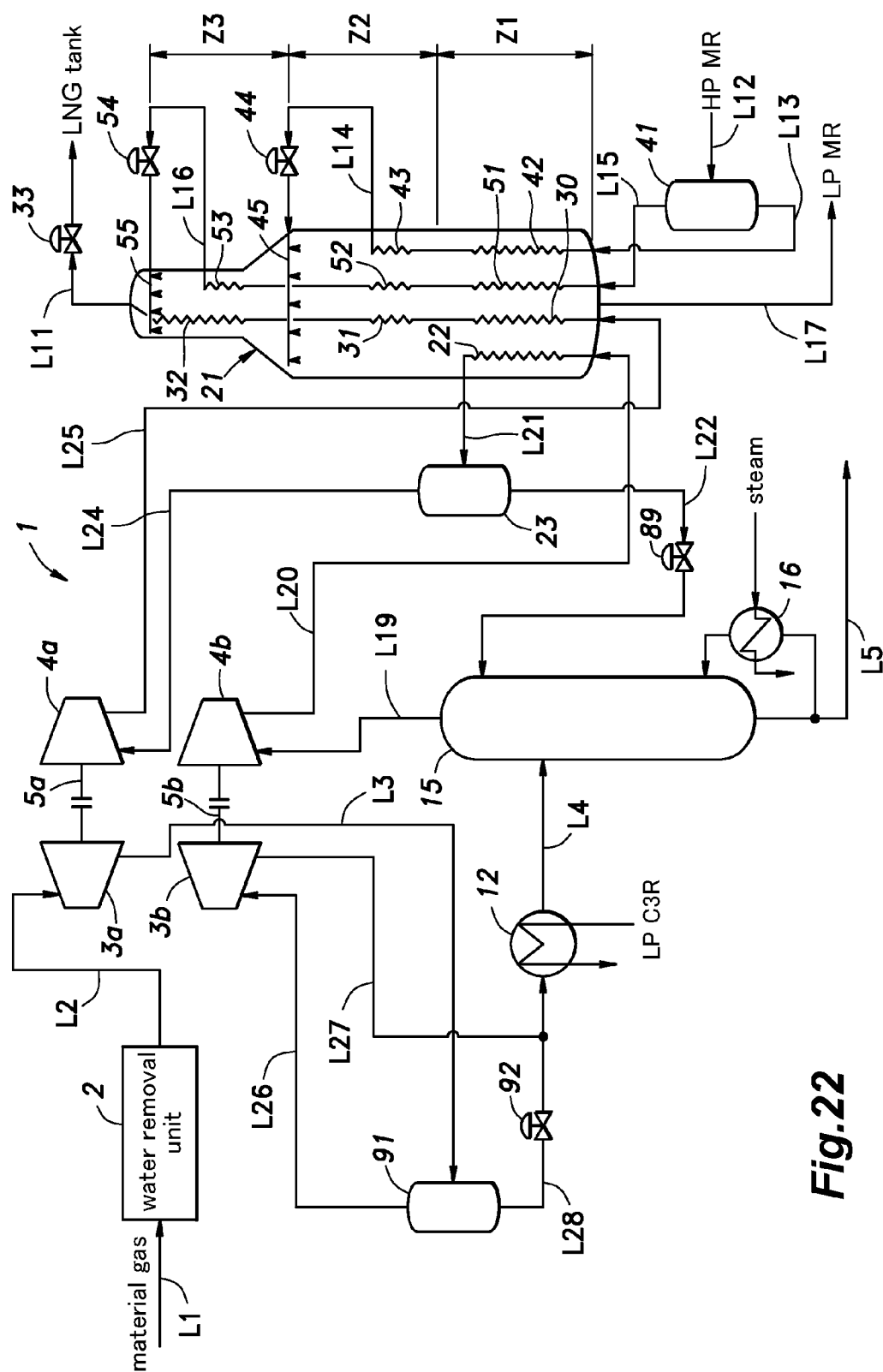
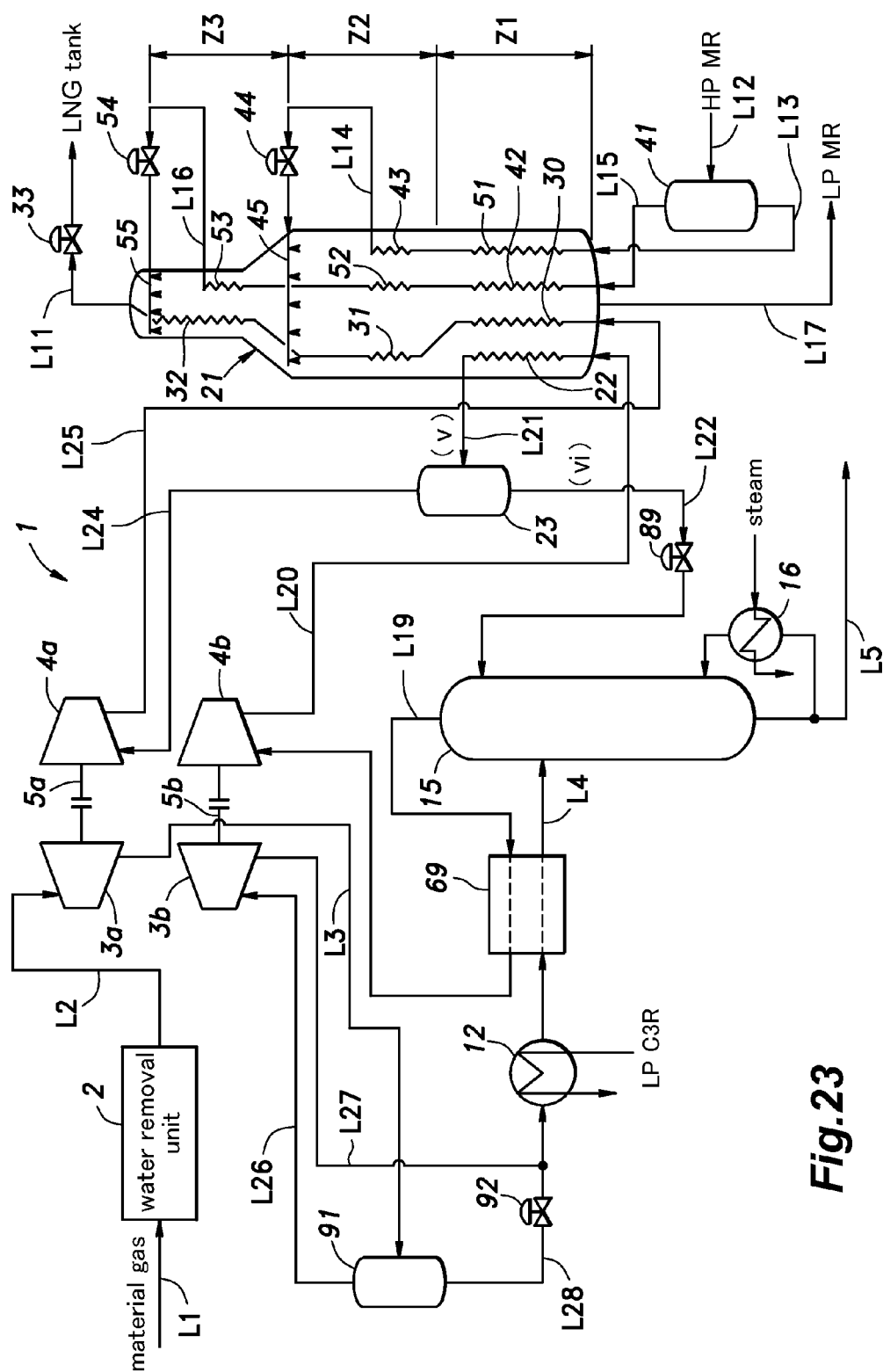


Fig. 22



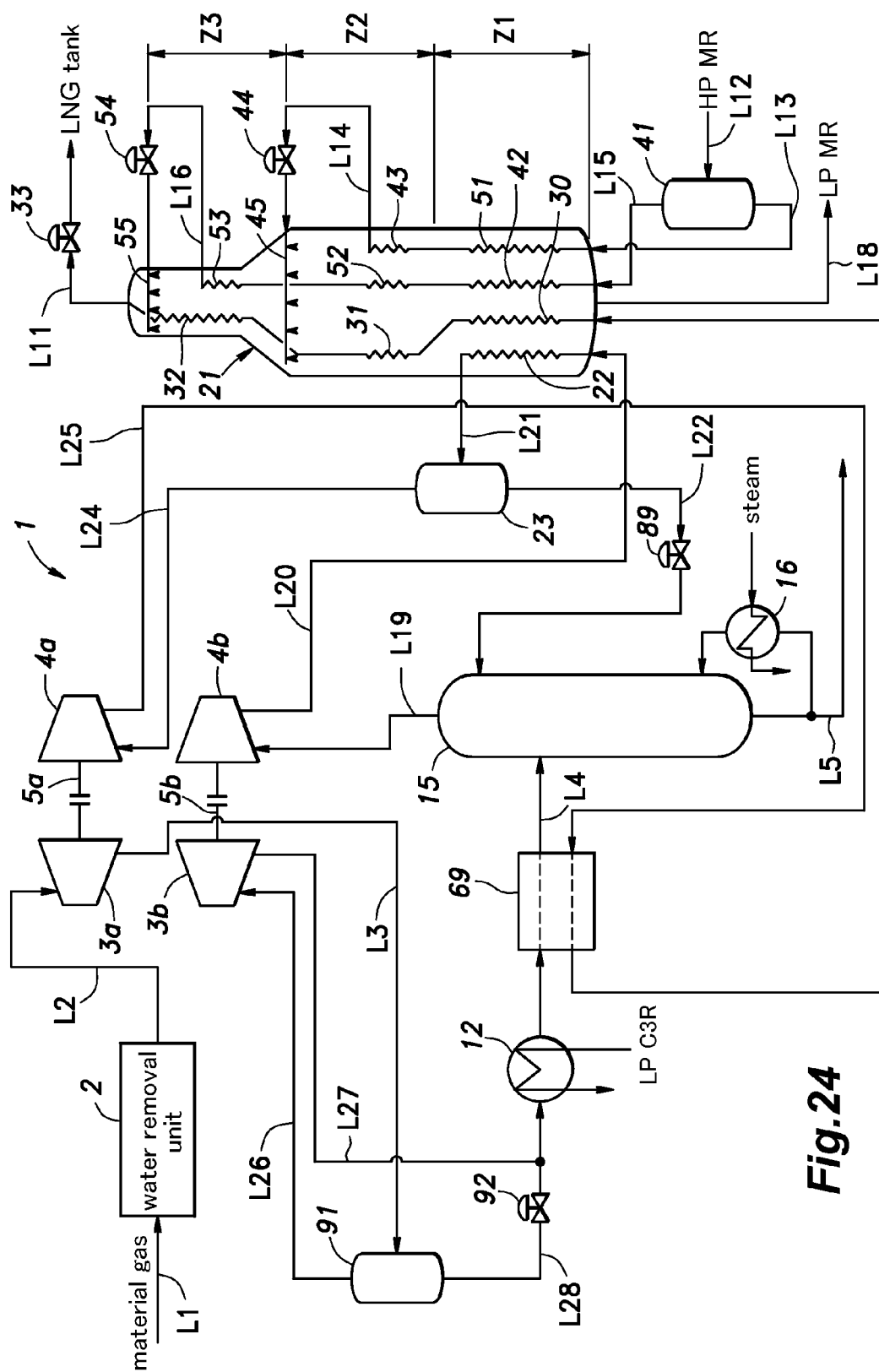
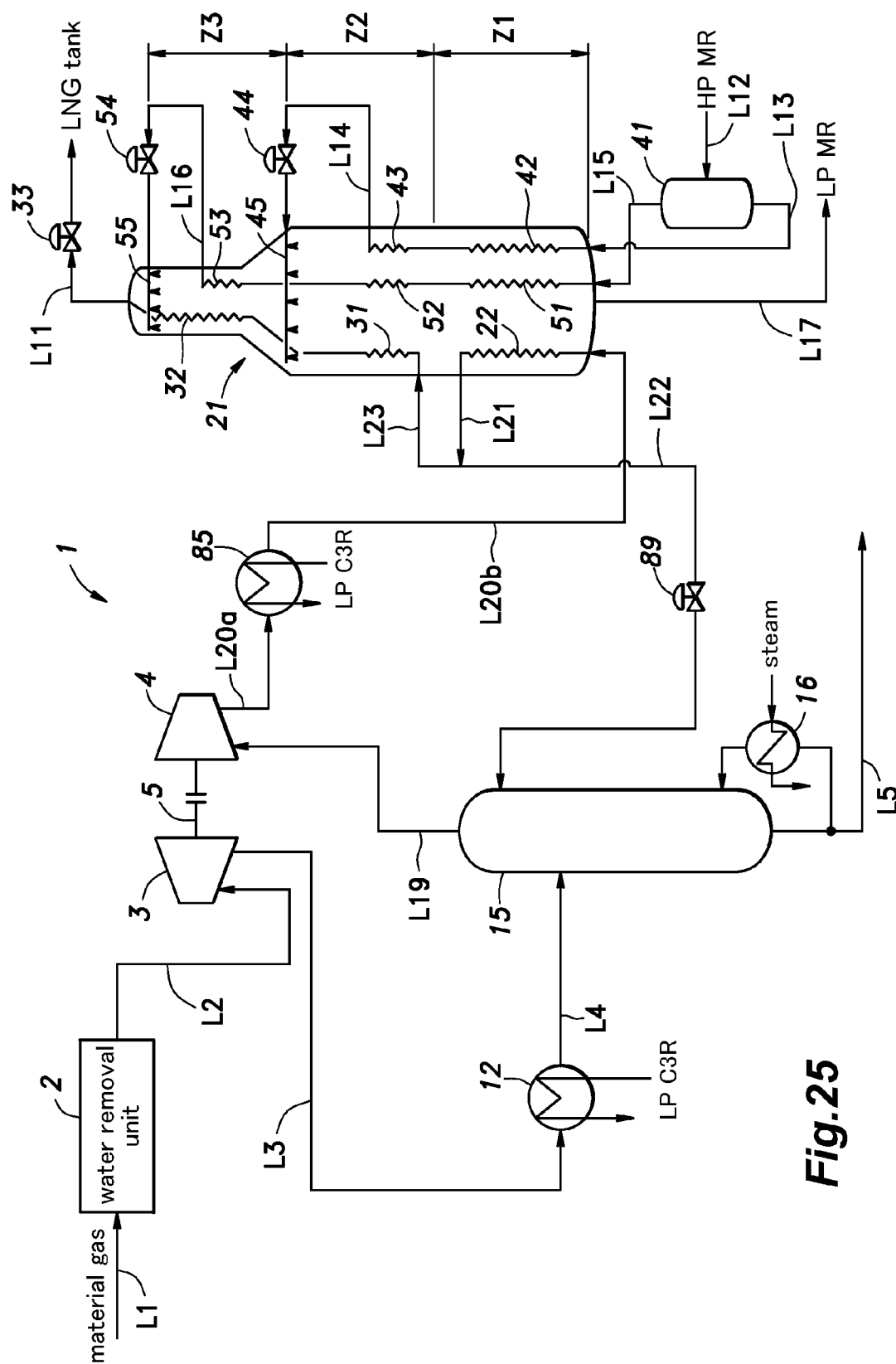


Fig.24



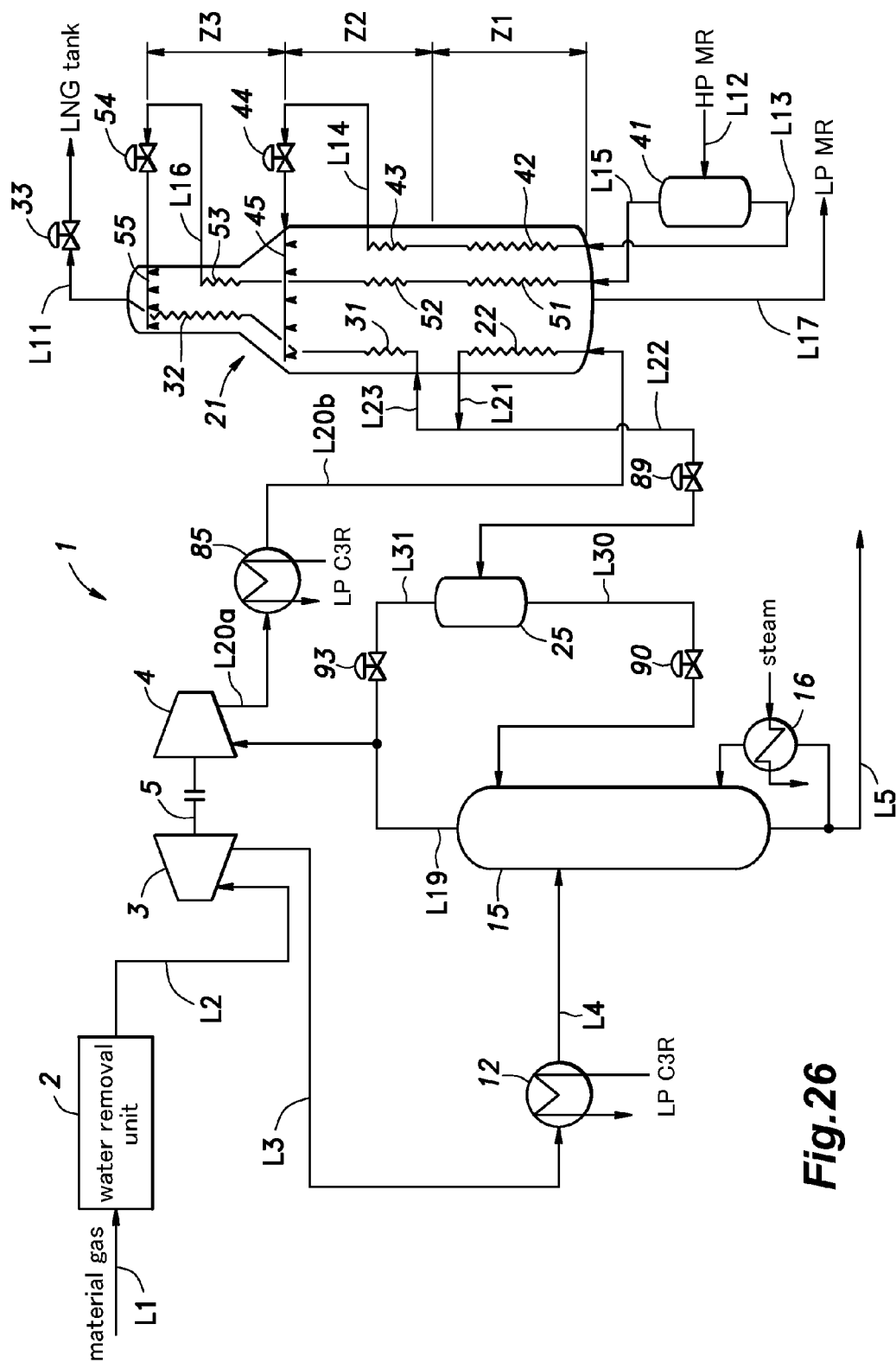
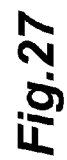


Fig.26



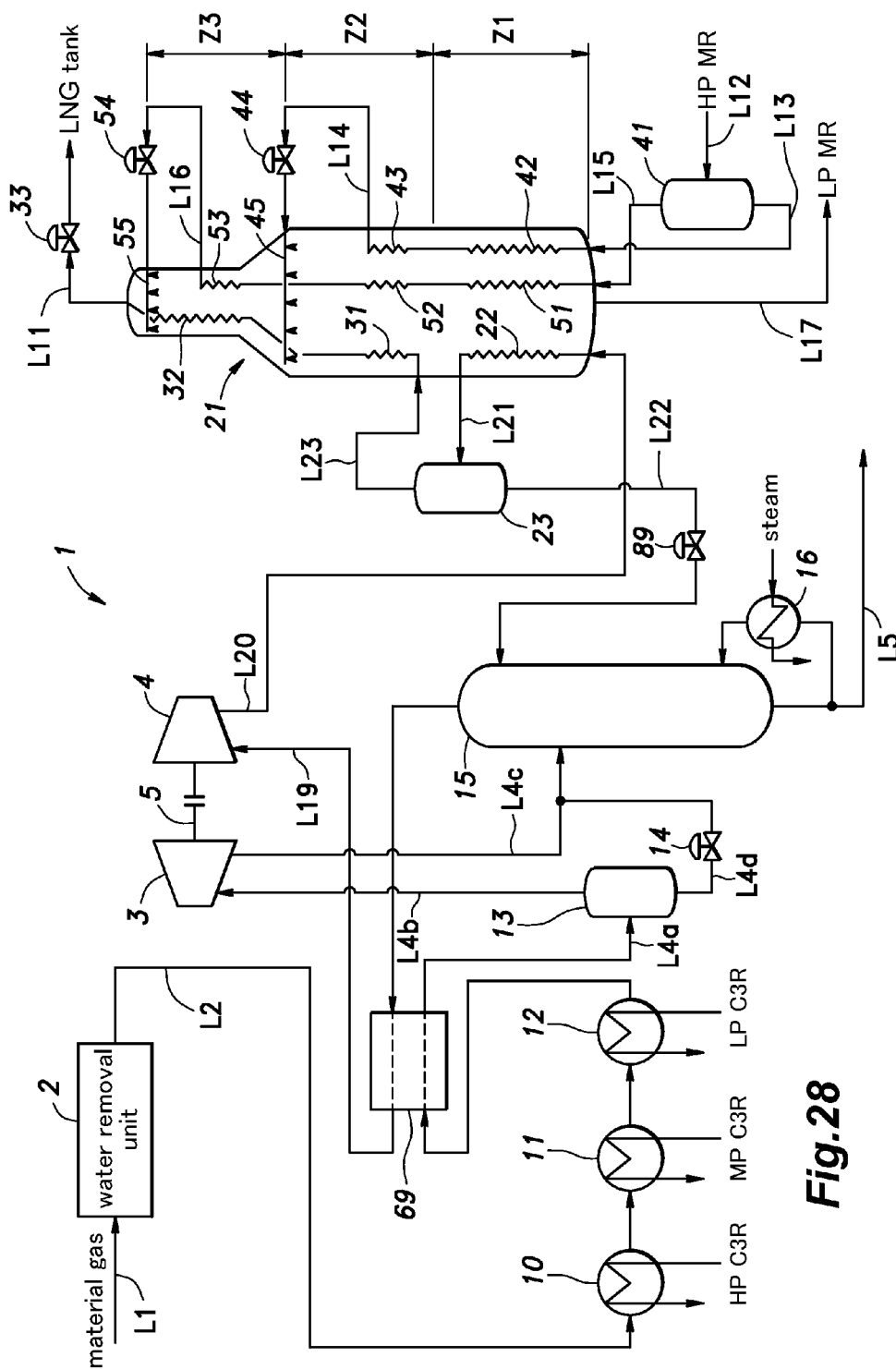
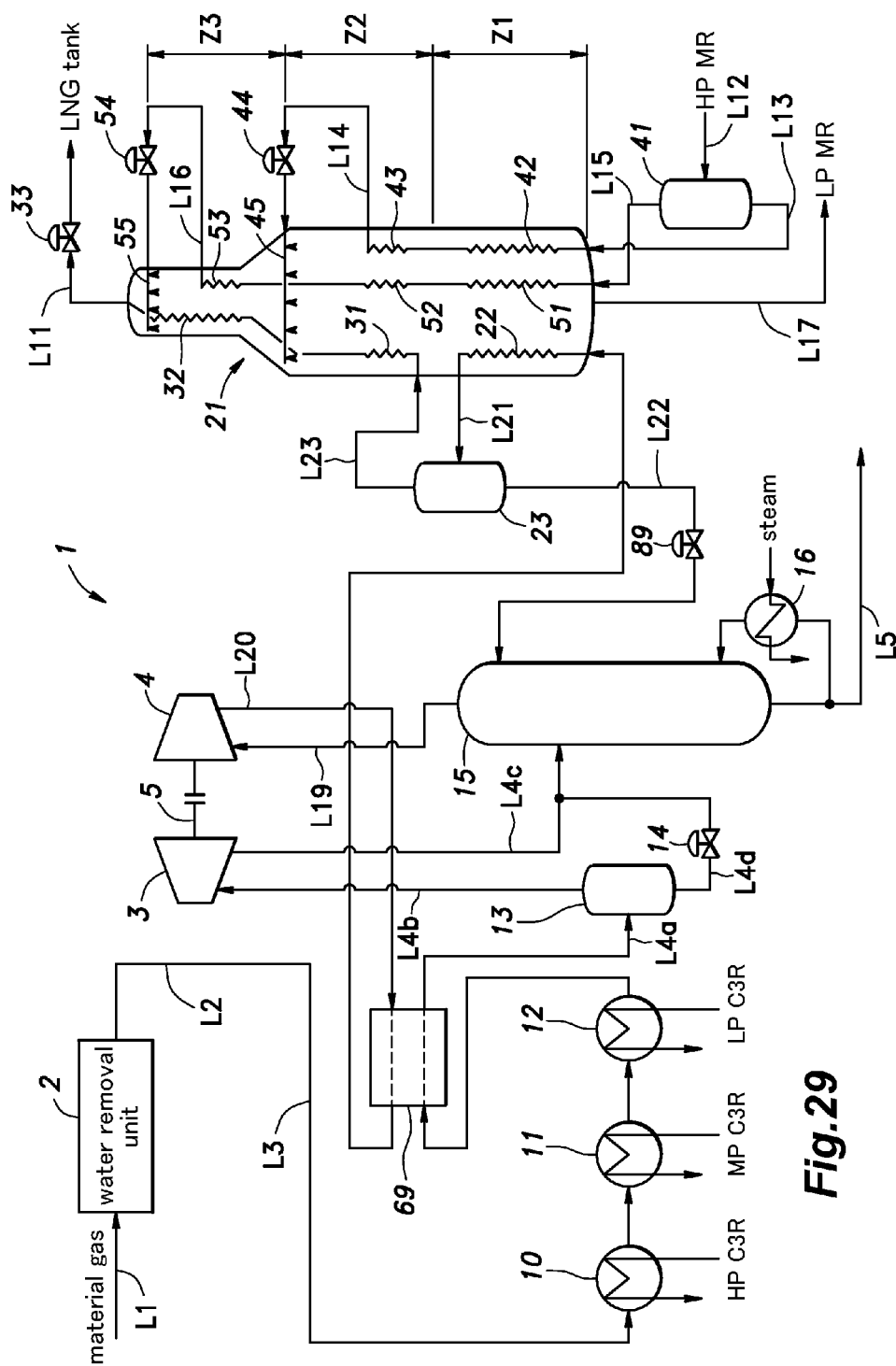


Fig.28



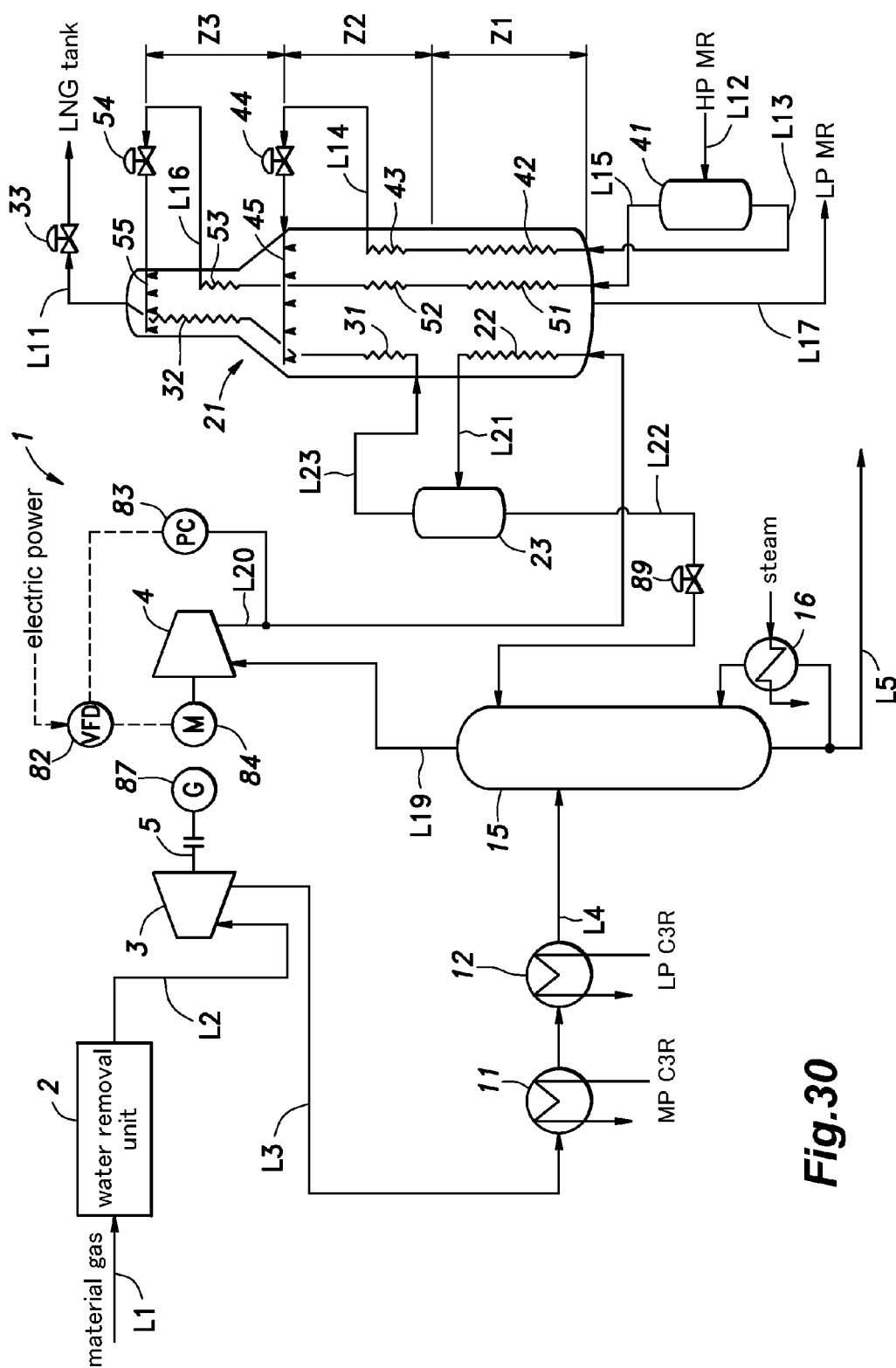


Fig.30

Fig.31

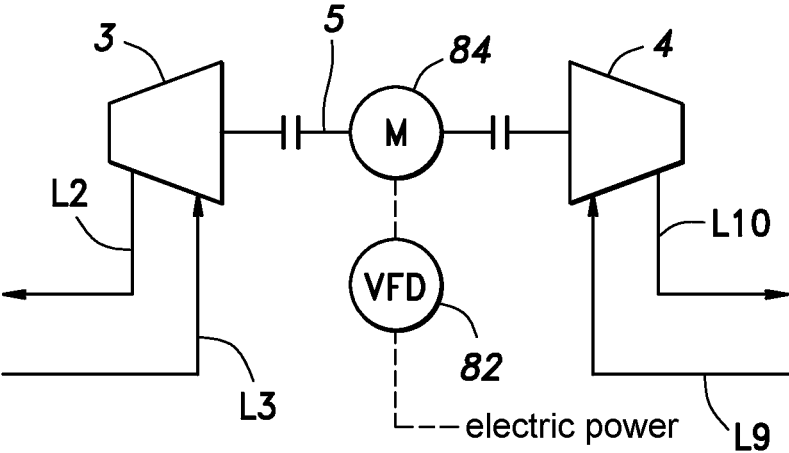
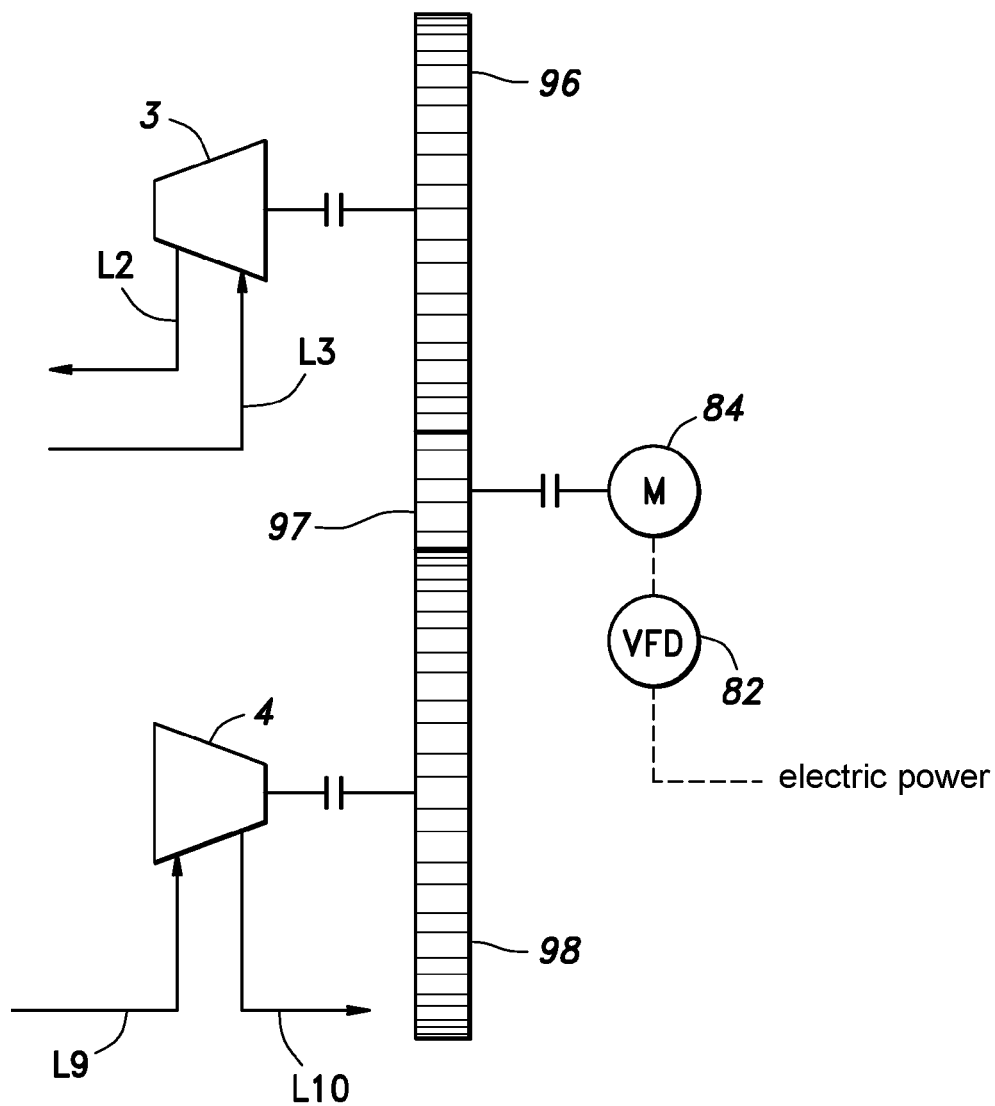


Fig.32



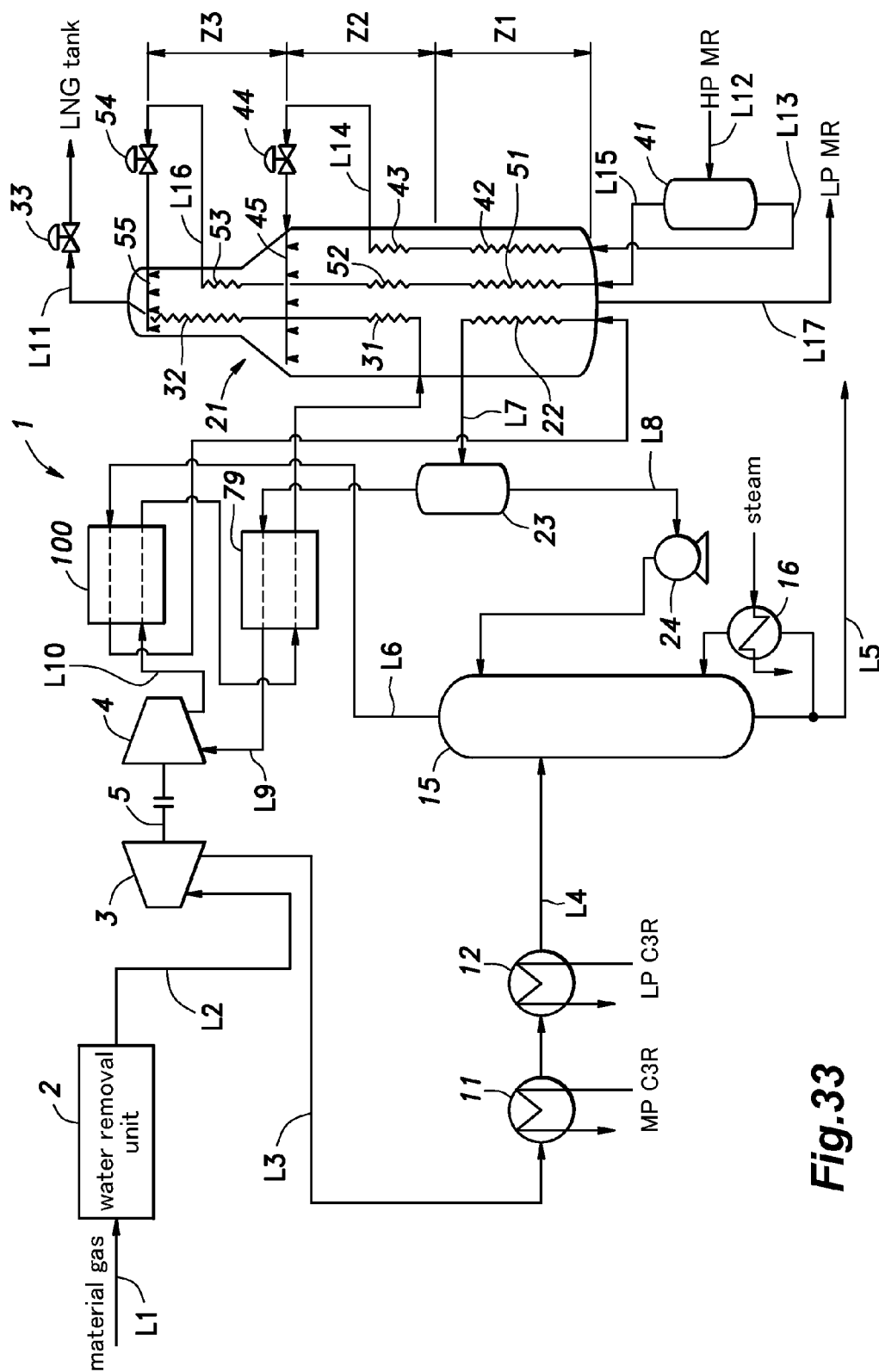


Fig.33

SYSTEM AND METHOD FOR LIQUEFACTION OF NATURAL GAS

TECHNICAL FIELD

[0001] The present invention relates to a system and a method for the liquefaction of natural gas for producing liquefied natural gas by cooling natural gas.

BACKGROUND ART

[0002] Natural gas obtained from gas fields is liquefied in a liquefaction plant so that the gas may be stored and transported in liquid form. Cooled to about -162 degrees Celsius, the liquid natural gas has a significantly reduced volume as compared to gaseous natural gas, and is not required to be stored under a high pressure. The natural gas liquefaction process at the same time removes impurities such as water, acid gases and mercury contained in the mined natural gas, and after heavier components having relatively high freezing points (C5+ hydrocarbons such as benzene, pentane and other heavier hydrocarbons are removed, the natural gas is liquefied.

[0003] Various technologies have been developed for liquefying natural gas, including those based on expansion processes using expansion valves and turbines and heat exchange processes using low boiling point refrigerants (such as light hydrocarbons such as methane, ethane and propane). For instance, a certain known natural gas liquefaction system (See Patent Document 1) comprises a cooling unit for cooling natural gas from which impurities are removed, an expansion unit for isentropically expanding the cooled natural gas, a distillation unit for distilling the natural gas depressurized by the expansion unit at a pressure lower than the critical pressures of methane and heavier contents, a compressor for compressing the distilled gas from the distillation unit by using the shaft output from the expander, and a liquefaction unit for liquefying the distilled gas compressed by the compressor by exchanging heat with a mixed refrigerant.

PRIOR ART DOCUMENT (S)

Patent Document(s)

[0004] Patent Document 1: U.S. Pat. No. 4,065,278

SUMMARY OF THE INVENTION

Task to be Accomplished by the Invention

[0005] In the conventional liquefaction systems for natural gas such as the one disclosed in Patent Document 1, the outlet pressure of the compressor (or the pressure of the feedstock gas that is to be introduced into the liquefaction unit) is desired to be as high as possible in order to reduce the load on the liquefaction unit (in particular, the main heat exchanger thereof) and maximize the efficiency of the liquefaction process.

[0006] In order to increase the outlet pressure of the compressor, a correspondingly large power is required. However, in the conventional arrangement where the feedstock gas cooled by a cooling unit is expanded by an expander, the power produced from the expander is limited, and is inadequate for increasing the outlet pressure of the compressor to the desired level.

[0007] In the conventional arrangement, because the feedstock gas is required to be cooled before being expanded in the expander, a relatively large capacity is required for the cooling unit, and this increases the initial costs and the running costs of the cooling unit.

[0008] In the conventional arrangement, because cooling of the feedstock gas will cause condensates to be produced, it is necessary to provide a gas-liquid separator to separate (remove) condensates from the feedstock gas before introducing the feedstock gas from the cooling unit to the expander. Furthermore, because the temperature of the feedstock gas at the outlet end of the compressor is high, a significant temperature difference arises between the intermediate inlet point of the liquefying unit and the refrigerant so that a correspondingly high capacity is required for the cooling unit.

[0009] In view of such problems of the prior art, a primary object of the present invention is to provide a system and a method for the liquefaction of natural gas which can increase the pressure at the outlet end of the compressor by using the power generated in the expander by the expansion of the feedstock gas, and minimize the cooling capacity that is required for the cooling unit.

Means to Accomplish the Task

[0010] A first aspect of the present invention provides a system (1) for the liquefaction of natural gas that cools the natural gas to produce liquefied natural gas, comprising: a first expander (3) for generating power by expanding natural gas under pressure as material gas; a first cooling unit (11, 12) for cooling the material gas depressurized by expansion in the first expander; a distillation unit (15) for reducing or eliminating a heavy component in the material gas by distilling the material gas cooled by the first cooling unit; a first compressor (4) for compressing the material gas from which the heavy component was reduced or eliminated by the distillation unit by using the power generated in the first expander; and a liquefaction unit (21) for liquefying the material gas compressed by the first compressor by exchanging heat with a refrigerant.

[0011] According to the first aspect of the present invention, the system for the liquefaction of natural gas allows the outlet pressure of the first compressor to be increased and the cooling capacity required for the first cooling unit to be reduced by making use of the power generated by the first expander owing to the expansion of the material gas before being cooled by the first cooling unit.

[0012] A second aspect of the present invention further comprises a second cooling unit (85) placed between the first compressor and the liquefaction unit to cool the material gas compressed by the first compressor.

[0013] According to the second aspect of the present invention, by increasing the pressure of the material gas that is introduced into the liquefaction unit, even when the temperature level of the material gas should exceed an appropriate range, owing to the cooling in the second cooling unit, the temperature level of the material gas can be adjusted to a level close to the temperature level at the introduction point in the liquefaction unit so that the load on the liquefaction unit can be reduced and the efficiency of the liquefaction process can be increased.

[0014] A third aspect of the present invention provides a system for the liquefaction of natural gas, wherein the liquefaction unit comprises a spool-wound heat exchanger,

and the material gas expelled from the first compressor is introduced into a warm region (Z1) of the spool-wound heat exchanger located on a hot side of the spool-wound heat exchanger.

[0015] According to the third aspect of the present invention, if the temperature of the material gas should increase owing to the increase in the outlet pressure of the first compressor, by introducing the material gas from the side of the warm region (Z1) of the spool-wound heat exchanger to bring the temperature level of the material gas closer to the temperature in the liquefaction unit, the load on the liquefaction unit can be reduced, and the efficiency of the liquefaction process can be increased.

[0016] A fourth aspect of the present invention provides a system for the liquefaction of natural gas, further comprising a second compressor (75) placed between the first compressor and the liquefaction unit for compressing the material gas expelled from the first compressor.

[0017] According to the fourth aspect of the present invention, the pressure of the material gas that is introduced into the liquefaction unit can be increased even further so that the efficiency of the liquefaction process performed in the liquefaction unit can be increased.

[0018] A fifth aspect of the present invention provides a system for the liquefaction of natural gas, further comprising a first electric motor (81) powered by an external electric power and controlled in dependence on a pressure value of the material gas introduced into the liquefaction unit, and the second compressor is driven by the first electric motor.

[0019] According to the fifth aspect of the present invention, the pressure of the material gas that is introduced into the liquefaction unit can be increased in a stable manner so that the temperature of the material gas can be maintained within an appropriate range and the liquefaction process can be performed in the liquefaction unit in a both efficient and stable manner.

[0020] A sixth aspect of the present invention provides a system for the liquefaction of natural gas, further comprising a second cooling unit (85) placed between the second compressor and the liquefaction unit to cool the material gas.

[0021] According to the sixth aspect of the present invention, by increasing the pressure of the material gas that is introduced into the liquefaction unit, even when the temperature level of the material gas should exceed an appropriate range, owing to the cooling in the second cooling unit, the temperature level of the material gas can be adjusted to a level close to the temperature level at the introduction point in the liquefaction unit so that the load on the liquefaction unit can be reduced, and the efficiency of the liquefaction process can be increased.

[0022] A seventh aspect of the present invention provides a system for the liquefaction of natural gas, further comprising an electric generator unit (87) for converting the power generated by the first expander into electric power and a second electric motor (84) for driving the first compressor, the second electric motor being powered by electric power generated by the electric generator unit.

[0023] According to the seventh aspect of the present invention, the first expander and the first compressor are electrically connected to each other so that the outlet pressure of the first compressor can be increased by making use of the power generated by the first expander. At the same time, the freedom in the mode of operation of the system can

be increased as compared to the case where the first expander and the first compressor are mechanically connected to each other.

[0024] An eighth aspect of the present invention provides a system for the liquefaction of natural gas, further comprising a second electric motor (84) mechanically coupling the first expander and the first compressor to each other and powered by external electric power, wherein the first compressor is configured to compress the material gas by using power generated by the first expander and the power generated by the second electric motor.

[0025] According to the eighth aspect of the present invention, the power provided by the second electric motor can be used for augmenting the power provided by the first expander in driving the first compressor so that the outlet pressure of the first compressor can be increased in a both efficient and stable manner.

[0026] A ninth aspect of the present invention provides a system for the liquefaction of natural gas, wherein the material gas from which the heavy component is reduced or eliminated by the distillation unit is directly introduced into the first compressor, and the system further comprises a first gas-liquid separation vessel (23) for receiving the material gas compressed by the first compressor via the liquefaction unit; and wherein a gas phase component of the material gas separated in the first gas-liquid separation vessel is introduced into the liquefaction unit once again, and a liquid phase component of the material gas is recirculated to the distillation unit.

[0027] According to the ninth aspect of the present invention, the need for a pump for recirculating the material gas from the first gas-liquid separation vessel to the distillation unit can be eliminated, and this contributes to the simplification of the system.

[0028] A tenth aspect of the present invention provides a system for the liquefaction of natural gas, further comprising a second cooling unit (85) placed between the first compressor and the first gas-liquid separation vessel to cool the material gas.

[0029] According to the tenth aspect of the present invention, even when the temperature level of the material gas that is compressed by the first compressor should exceed an appropriate range, owing to the cooling in the second cooling unit, the temperature level of the material gas can be adjusted to a level close to the temperature level at the introduction point in the liquefaction unit so that the load on the liquefaction unit can be reduced, and the efficiency of the liquefaction process can be increased.

[0030] An eleventh aspect of the present invention provides a system for the liquefaction of natural gas, further comprising a second expander (3b) placed between the first expander (3a) and the distillation unit to generate power by expanding the material gas, and a third compressor (4b) placed between the distillation unit and the first compressor (4a) to compress the material gas distilled by the distillation unit by using the power generated by the second expander.

[0031] According to the eleventh aspect of the present invention, by advantageously expanding the material gas in the first and second expanders, the cooling capacity required for the first cooling unit can be reduced, and by using the first and third compressors that make use of the power generated by the first and second expanders, the pressure of the material gas that is introduced into the liquefaction unit can be effectively increased.

[0032] A twelfth aspect of the present invention provides a system for the liquefaction of natural gas, further comprising a second expander (3b) placed in parallel with the first expander (3a) to generate power by expanding the material gas, and a third compressor (4b) placed between the distillation unit and the first compressor (4a) to compress the material gas distilled by the distillation unit by using the power generated by the second expander.

[0033] According to the twelfth aspect of the present invention, even when the volume of the material gas introduced into the liquefaction system should increase, the liquefaction process in the liquefaction unit can be performed in a stable manner.

[0034] A thirteenth aspect of the present invention provides a system for the liquefaction of natural gas, wherein the liquefaction unit comprises a plate-fin heat exchanger.

[0035] According to the thirteenth aspect of the present invention, even when the temperature level of the material gas that is compressed by the first compressor should rise with the rise in the pressure thereof, the point of introduction into the liquefaction unit (the temperature level on the side of the liquefaction unit) can be changed in response to the rise in the temperature of the material gas with ease.

[0036] A fourteenth aspect of the present invention provides a system for the liquefaction of natural gas, wherein the material gas compressed by the first compressor has a pressure higher than 5,171 kPaA.

[0037] A fifteenth aspect of the present invention provides a system for the liquefaction of natural gas, wherein the material gas compressed by the second expander has a pressure higher than 5,171 kPaA.

[0038] According to the fourteenth or fifteenth aspect of the present invention, by raising the pressure of the material gas that is introduced into the liquefaction unit to an appropriate value, the efficiency of the liquefaction process in the liquefaction unit can be increased.

[0039] A sixteenth aspect of the present invention provides a system for the liquefaction of natural gas, further comprising a heat exchanger (69) for exchanging heat between the material gas introduced into the distillation unit and a top fraction from the distillation unit.

[0040] According to the sixteenth aspect of the present invention, even when the temperature of the material gas that is introduced into the liquefaction unit is lower than an appropriate range, the temperature of the material gas can be brought close the temperature at the inlet end of the liquefaction unit by heating the top fraction of the distillation unit by exchanging heat with the material gas that is introduced into the distillation unit.

[0041] A seventeenth aspect of the present invention provides a system for the liquefaction of natural gas, further comprising a first gas-liquid separation vessel (23) for receiving a top fraction from the distillation unit, and a third cooling unit (86) placed between the distillation unit and the first gas-liquid separation vessel to cool the top fraction from the distillation unit.

[0042] According to the seventeenth aspect of the present invention, the need to cooling the material gas that is to be introduced into the first gas-liquid separation vessel by using the liquefaction unit is eliminated so that the load on the liquefaction unit is reduced.

[0043] An eighteenth aspect of the present invention provides a system for the liquefaction of natural gas, further comprising a second heat exchanger (79) for exchanging

heat between the material gas to be introduced into the first compressor and the material gas compressed by the first compressor.

[0044] According to the eighteenth aspect of the present invention, even when the temperature of the material gas that is compressed by the first compressor and introduced into the liquefaction unit is higher than an appropriate range, the temperature of the material gas can be brought close the temperature at the inlet end of the liquefaction unit by cooling the material gas from the first compressor by exchanging heat with the material gas that is introduced into the first compressor.

[0045] A nineteenth aspect of the present invention provides a system for the liquefaction of natural gas, comprising a fifth cooling unit (80) for cooling the material gas compressed by the first compressor at a point upstream of the second heat exchanger by using a water, air or a propane refrigerant.

[0046] According to the nineteenth aspect of the present invention, even when the temperature of the material gas that is compressed by the first compressor and introduced into the liquefaction unit is higher than an appropriate range, the temperature of the material gas can be brought close the temperature at the inlet end of the liquefaction unit by cooling the material gas from the first compressor by using the fifth cooling unit. In particular, by cooling the material gas with propane having a relatively high cooling capacity, the freedom in the operation of the compression process of the material gas with the first compressor can be enhanced.

[0047] A twentieth aspect of the present invention provides a system for the liquefaction of natural gas, further comprising a third heat exchanger (100) for exchanging heat between the material gas compressed by the first compressor and the top fraction from the distillation unit.

[0048] According to the twentieth aspect of the present invention, even when the temperature of the material gas that is compressed by the first compressor and introduced into the liquefaction unit is higher than an appropriate range, the temperature of the material gas can be brought close the temperature at the inlet end of the liquefaction unit by cooling the material gas from the first compressor by exchanging heat with the top fraction of the distillation unit.

[0049] A twenty first aspect of the present invention provides a system (1) for the liquefaction of natural gas that cools the natural gas to produce liquefied natural gas, comprising: a first expander (3) for generating power by expanding natural gas under pressure as material gas; a distillation unit (15) for reducing or eliminating a heavy component in the material gas by distilling the material gas depressurized by expansion in the first expander; a first compressor (4) for compressing the material gas from which the heavy component was reduced or eliminated by the distillation unit by using power generated in the first expander; and a liquefaction unit (21) for liquefying the material gas compressed by the first compressor by exchanging heat with a refrigerant.

[0050] According to the twenty first aspect of the present invention, in conjunction with the liquefaction of material gas at a relatively high pressure (100 barA or higher, for instance), the power generated by the first expander owing to the expansion of the material gas can be used for increasing the outlet pressure of the first compressor.

[0051] A twenty second aspect of the present invention provides a system (1) for the liquefaction of natural gas that

cools the natural gas to produce liquefied natural gas, comprising: a first expander (3) for generating power by expanding natural gas under pressure as material gas; a first cooling unit (10, 11, 12) for cooling the material gas at least at a point upstream or downstream of the first expander; a distillation unit (15) for reducing or eliminating a heavy component in the material gas by distilling the material gas cooled by the first cooling unit; a first compressor (4) for compressing the material gas from which the heavy component was reduced or eliminated by the distillation unit; and a liquefaction unit (21) for liquefying a gas phase component separated from the material gas compressed by the first compressor by exchanging heat with a refrigerant.

[0052] According to the twenty second aspect of the present invention, the material gas that is compressed by the compressor and introduced into the liquefaction unit is prevented from rising excessively in temperature, and the temperature of the material gas can be adjusted to be close the temperature at the inlet end of the liquefaction unit with ease.

[0053] A twenty third aspect of the present invention provides a system for the liquefaction of natural gas, further comprising a first gas-liquid separation vessel (23) for receiving the material gas compressed by the first compressor and a second cooling unit (85) provided between the first compressor and the first gas-liquid separation vessel for cooling the compressed gas expelled from the first compressor.

[0054] According to the twenty third aspect of the present invention, the material gas that is to be introduced into the first gas-liquid separation vessel is not required to be cooled by the liquefaction unit so that the load on the liquefaction unit can be reduced.

[0055] A twenty fourth aspect of the present invention provides a system for the liquefaction of natural gas, further comprising a second gas-liquid separation vessel (25) for receiving a part of the compressed gas that is compressed and separated by the first compressor, and a liquid phase component separated by the second gas-liquid separation vessel is recirculated to the distillation unit.

[0056] According to the twenty fourth aspect of the present invention, even when the critical pressure of the material gas is relatively low, and the pressure of the material gas that is to be processed by the liquefaction system is higher than the critical pressure, the liquefaction load of the liquefaction unit can be reduced, and the process stability of the distillation unit can be enhanced.

[0057] A twenty fifth aspect of the present invention provides a system for the liquefaction of natural gas, further comprising a heat exchanger (69) for exchanging heat between the material gas that is introduced into the distillation unit and a top fraction from the distillation unit.

[0058] According to the twenty fifth aspect of the present invention, even when the temperature of the material gas that is introduced into the liquefaction unit is lower than an appropriate range, the temperature of the material gas can be brought close the temperature at the inlet end of the liquefaction unit (21) by warming the top fraction of the distillation unit by exchanging heat with the material gas that is to be introduced into the distillation unit.

[0059] A twenty sixth aspect of the present invention provides a method for the liquefaction of natural gas by cooling the natural gas to produce liquefied natural gas, comprising: a first expansion step for generating power by

using natural gas under pressure as material gas; a first cooling step for cooling the material gas depressurized by expansion in the first expansion step; a distillation step for reducing or eliminating a heavy component in the material gas by distilling the material gas cooled in the first cooling step; and a first compression step for compressing the material gas from which the heavy component was reduced or eliminated in the distillation step by using the power generated in the first expansion step; and a liquefaction step for liquefying the material gas compressed in the first compression step by exchanging heat with a refrigerant.

[0060] A twenty seventh aspect of the present invention provides a method for the liquefaction of natural gas by cooling the natural gas to produce liquefied natural gas, comprising: a first expansion step for generating power by expanding natural gas under pressure as material gas; a first cooling step for cooling the material gas at least before or after the first expansion step; a distillation step for reducing or eliminating a heavy component in the material gas by distilling the material gas cooled in the first cooling step; a first compression step for compressing the material gas from which the heavy component was reduced or eliminated in the distillation step; and a liquefaction step for liquefying a gas phase component separated from the material gas compressed in the first compression step by exchanging heat with a refrigerant.

Effect of the Invention

[0061] As can be appreciated from the foregoing, the liquefaction system for the liquefaction of natural gas according to the present invention allows the outlet pressure of the compressor to be increased by using the power generated by the expander owing to the expansion of the material gas, and the cooling capacity that is required for the cooling unit to be reduced.

BRIEF DESCRIPTION OF THE DRAWINGS

[0062] FIG. 1 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a first embodiment of the present invention;

[0063] FIG. 2 is a diagram showing a liquefaction process flow in a conventional system for the liquefaction of natural gas given as a first example for comparison;

[0064] FIG. 3 is a diagram showing a liquefaction process flow in a conventional system for the liquefaction of natural gas given as a second example for comparison;

[0065] FIG. 4 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a first modification of the first embodiment;

[0066] FIG. 5 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a second modification of the first embodiment;

[0067] FIG. 6 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a third modification of the first embodiment;

[0068] FIG. 7 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a fourth modification of the first embodiment;

[0069] FIG. 8 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a fifth modification of the first embodiment;

[0070] FIG. 9 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a sixth modification of the first embodiment;

[0071] FIG. 10 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a seventh modification of the first embodiment;

[0072] FIG. 11 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a second embodiment of the present invention;

[0073] FIG. 12 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a third embodiment of the present invention;

[0074] FIG. 13 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a modification of the third embodiment;

[0075] FIG. 14 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a fourth embodiment of the present invention;

[0076] FIG. 15 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a fifth embodiment of the present invention;

[0077] FIG. 16 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a sixth embodiment of the present invention;

[0078] FIG. 17 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a first modification of the sixth embodiment;

[0079] FIG. 18 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a second modification of the sixth embodiment;

[0080] FIG. 19 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a third modification of the sixth embodiment;

[0081] FIG. 20 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a fourth modification of the sixth embodiment;

[0082] FIG. 21 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a seventh embodiment of the present invention;

[0083] FIG. 22 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as an eighth embodiment of the present invention;

[0084] FIG. 23 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a first modification of the eighth embodiment;

[0085] FIG. 24 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a second modification of the eighth embodiment;

[0086] FIG. 25 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a ninth embodiment of the present invention;

[0087] FIG. 26 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a modification of the ninth embodiment;

[0088] FIG. 27 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a tenth embodiment of the present invention;

[0089] FIG. 28 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a first modification of the tenth embodiment;

[0090] FIG. 29 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a second modification of the tenth embodiment;

[0091] FIG. 30 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as an eleventh embodiment of the present invention;

[0092] FIG. 31 is a diagram showing a first variation of the connecting arrangement between the expander and the compressor in the system for the liquefaction of natural gas according to the present invention;

[0093] FIG. 32 is a diagram showing a second variation of the connecting arrangement between the expander and the compressor in the system for the liquefaction of natural gas according to the present invention; and

[0094] FIG. 33 is a diagram showing the liquefaction flow in the system for the liquefaction of natural gas of an eighth modification of the first embodiment.

DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

[0095] Preferred embodiments of the present invention are described in the following with reference to the appended drawings.

First Embodiment

[0096] FIG. 1 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a first embodiment of the present invention. Table 1 which will be shown hereinafter lists the results of a simulation of the liquefaction process in the system for the liquefaction of natural gas. The same is similarly true with Tables 2 to 12. Table 1 shows the temperature, the pressure, the flow rate and the molar composition of the natural gas that is to be liquefied at each of various points in the liquefaction system of the first embodiment. In Table 1, columns (i) to (ix) show the values at the respective points in the liquefaction system 1 denoted with corresponding roman numerals (i) to (ix) in FIG. 1.

[0097] Natural gas containing about 80 to 98 mol % of methane is used as the material gas or the feedstock gas. The material gas also contains at least C5+ hydrocarbons by at least 0.1 mol % or BTX (benzene, toluene, xylene) by at least 1 ppm mol as heavier contents. The contents of the material gas other than methane are shown in column (i) of Table 1. The term "material gas" as used in this specification is not necessarily required to be in gaseous form, but may also be in liquid form according to various stages of liquefaction.

[0098] In this liquefaction system 1, the material gas is supplied to a water removal unit 2 via a line L1, and is freed from moisture in order to avoid troubles due to icing. The material gas supplied to the water removal unit 2 has a temperature of about 20 degrees Celsius, a pressure of about 5,830 kPaA and a flow rate of about 720,000 kg/hr. The water removal unit 2 may consist of towers filled with desiccant (such as a molecular sieve), and can reduce the water content of the material gas to less than 0.1 ppm mol. The water removal unit 2 may consist of any other known unit which is capable of removing water from the material gas below a desired level.

[0099] Although detailed discussion is omitted here, the liquefaction system 1 may employ additional known facilities for performing preliminary process steps preceding the process step in the water removal unit 2, such as a separation unit for removing natural gas condensate, an acid gas removal unit for removing acid gases such as carbon dioxide

and hydrogen sulfide and a mercury removal unit for removing mercury. Typically, the water removal unit **2** receives material gas from which impurities are removed by using such facilities. The material gas that is supplied to the water removal unit **2** is pre-processed such that the carbon dioxide (CO₂) content is less than 50 ppm mol, the hydrogen sulfide (H₂S) content is less than 4 ppm mol, the sulfur content is less than 20 mg/Nm³, and the mercury content is less than 10 ng/Nm³.

[0100] The source of the material gas may not be limited to any particular source, but may be obtained, not exclusively, from shale gas, tight sand gas and coal head methane in a pressurized state. The material gas may be supplied not only from the source such as a gas field via piping but also from storage tanks.

[0101] The material gas from which water is removed in the water removal unit **2** is forwarded to a first expander **3** via a line **L2**. The first expander **3** consists of a turbine for reducing the pressure of the natural gas supplied thereto, and obtaining power (or energy) from the expansion of the natural gas under an isentropic condition. Owing to the expansion step (first expansion step) in the first expander **3**, the pressure and the temperature of the material are reduced. The first expander **3** is provided with a common shaft **5** to a first compressor **4** (which will be discussed hereinafter) so that the power generated by the first expander **3** can be used for powering the first compressor **4**. If the rotational speed of the first expander **3** is lower than that of the first compressor **4**, a suitable step-up gear unit may be placed between the first expander **3** and the first compressor **4**. The first expander **3** reduces the temperature and the pressure of the material gas to about 8.3 degrees Celsius, a pressure of about 4,850 kPaA, respectively. Typically, the pressure of the material gas expelled from the first expander **3** is in the range of 3,000 kPaA to 5,500 kPaA (30 barA to 55 barA), or more preferably in the range of 3,500 kPaA to 5,000 kPaA (35 barA to 50 barA).

[0102] The material gas from the first expander **3** is forwarded a cooler **11** via a line **L3**. A cooling unit (first cooling unit) is formed by connecting another cooler **12** to the downstream end of the cooler **11**. The material gas is cooled by exchanging heat with refrigerants (first cooling step) in the first cooling unit **11, 12** in stages. The temperature of the material gas which has been cooled by the first cooling unit **11, 12** is in the range of from -20 to -50 degrees Celsius, or more preferably in the range of from -25 to -35 degrees Celsius. If the material gas introduced into the liquefaction system **1** is relatively high (higher than 100 barA, for instance), the first cooling unit **11, 12** may be omitted as the temperature of the material gas at the outlet of the first expander **3** is relatively low (-30 degrees Celsius, for instance). The possibility of omitting the cooling unit on the upstream side of the distillation unit **15** applies equally to the embodiments illustrated in FIGS. **4** to **26, 30** and **33** which will be discussed hereinafter.

[0103] In the present embodiment, the C3-MR (propane (C3) pre-cooled mixed refrigerant) system is used. The material gas is pre-cooled in the first cooling unit **11, 12** by using propane as the refrigerant, and is later super-cooled to an extremely low temperature for the liquefaction of the material gas in a refrigeration cycle using mixed refrigerants as will be discussed hereinafter. Propane refrigerants (C3R) for medium pressure (MP) and low pressure (LP) are used for cooling the material gas in a plurality of stages (in two stages in the illustrated embodiment) in the first cooling unit **11, 12**. Although not shown in the drawings, the first cooling

unit **11, 12** forms a part of a per se known refrigeration cycle including compressors and condensers for the propane refrigerants.

[0104] The liquefaction system **1** is not necessarily required to be based on the C3-MR system, but may use a cascade system in which a plurality of individual refrigeration cycles are formed by using corresponding refrigerants (such as methane, ethane and propane) having different boiling points, a DMR (double mixed refrigerant) system using a mixed medium such as a mixture of ethane and propane for a preliminary cooling process, and a MFC (mixed fluid cascade system) using different mixed refrigerants separately for the individual cycles of preliminary cooling, liquefaction and super cooling, among other possibilities.

[0105] The material gas from the cooler **12** is forwarded to the distillation unit **15** via a line **L4**. The pressure of the material gas at this point should be below the critical pressures of methane and heavier components by means of the expansion in the first expander **3** and other optional processes. The distillation unit **15** essentially consists of a distillation tower internally provided with a plurality of shelves for removing heavier contents in the material gas (distillation step). The liquid consisting of the heavier contents is expelled via a line **L5** connected to the bottom end of the distillation tower of the distillation unit **15**. The liquid consisting of the heavier contents that is expelled from the distillation unit **15** via the line **L5** has a temperature of about 177 degrees Celsius and a flow rate of about 20,000 kg/hr. The term "heavier contents" refer to components such as benzene having high freezing points and components having lower boiling points such as C5+ hydrocarbons. The line **L5** includes a recirculation unit including a reboiler **16** for heating a part of the liquid expelled from the bottom of the distillation tower of the distillation unit **15** by exchanging heat with steam (or oil) supplied to the reboiler **16** from outside, and recirculating the heated liquid back to the distillation unit **15**.

[0106] The top fraction from the distillation unit **15** consisting of the lighter components of the material gas primarily consists of methane having a low boiling point, and this material gas is introduced into the liquefaction unit **21** via the line **L6** to be cooled in the piping systems **22a** and **22b**. The material gas forwarded to the line **L5** has a temperature of about -45.6 degrees Celsius and a pressure of about 4,700 kPaA. The material gas freed from the heavier components in the distillation unit **15** contains less than 0.1 mol % of C5+ and less than 1 ppm mol of BTX (benzene, toluene and xylene). By flowing through the piping systems **22a** and **22b**, the material gas is cooled to about -65.2 degrees Celsius, and is then forwarded from the liquefaction unit **21** to a first gas-liquid separation vessel **23** via a line **L7**.

[0107] As will be discussed hereinafter, the liquefaction unit **21** essentially consists of a main heat exchanger in the liquefaction system **1**, and this heat exchanger consists of a spool-wound type heat exchanger including a shell and coils of heat transfer tubes for conducting the material gas and the refrigerant. The liquefaction unit **21** defines a warm region **Z1** situated in the lower part thereof for receiving the mixed refrigerant and having a highest temperature (range), an intermediate region **Z2** situated in the intermediate part thereof and having a lower temperature than the warm region **Z1** and a cold region situated in the upper part thereof for expelling the liquefied material gas and having a lowest temperature. In the first embodiment, the warm region **Z1** consists of a higher warm region **Z1a** on a higher temperature side and a lower warm region **Z1b** on a lower temperature

ture side. The piping systems **22a** and **22b**, as well as the piping systems **42a**, **51a**, and **42b** and **51b** through which the mixed refrigerant is conducted, are formed by the tube bundles provided in the higher warm region **Z1a** and the lower warm region **Z1b**, respectively. In the illustrated embodiment, the temperature of the higher warm region **Z1a** is about -35 degrees Celsius on the upstream side (inlet side) of the material gas that is to be cooled, and about -50 degrees Celsius on the downstream side (outlet side) of the material gas. The temperature of the lower warm region **Z1b** is about -50 degrees Celsius on the upstream side of the material gas, and about -135 degrees Celsius on the downstream side of the material gas. The temperature of the intermediate region **Z2** is about -65 degrees Celsius on the upstream side of the material gas, and about -135 degrees Celsius on the downstream side of the material gas. The temperature of the cold region **Z3** is about -135 degrees Celsius on the upstream side of the material gas, and about -155 degrees Celsius on the downstream side of the material gas. The temperatures on the upstream side and the downstream side of each region are not limited to the values mentioned here, and the temperature in each of these parts may vary within a prescribed range (± 5 degrees Celsius, for instance).

[0108] The first gas-liquid separation vessel **23** separates the liquid phase component (condensate) of the material gas, and this liquid essentially consisting of hydrocarbons is recirculated back to the distillation unit **15** by a recirculation pump **24** provided in a line **L8**. The gas phase component of the material gas obtained in the first gas-liquid separation vessel **23** and mainly consisting of methane is forwarded to a first compressor **4** via a line **L9**. The material gas is passed through the line **L8** at a flow rate of about $83,500$ kg/hr, and is passed through the line **L6** at a flow rate of about $780,000$ kg/hr. The first gas-liquid separation vessel **23** may also be cooled by using a mixed refrigerant or an ethylene refrigerant.

[0109] The first compressor **4** consists of a single stage centrifugal compressor having turbine blades for compressing the material gas, mounted on a shaft **5** common to the first expander **3**. The material gas compressed by the first compressor **4** (first compression step) is introduced into the liquefaction unit **21** via a line **L10**. The material gas that is put out by the first compressor **4** to the line **L10** has a temperature of about -51 degrees Celsius and a pressure of about $5,500$ kPaA. The material gas introduced into the liquefaction unit **21** is compressed by the first compressor **4** preferably to a pressure exceeding at least $5,171$ kPaA.

[0110] A line **L10** is connected to a piping system **30** positioned in the warm region **Z1b** of the liquefaction unit **21**, and the upstream end of this piping system **30** is connected to a piping system **31** in the intermediate region **Z2**, and then to a piping system **32** positioned in the cold region **Z3**. After being liquefied and super cooled by flowing through the piping systems **31** and **32**, the natural gas is forwarded to an LNG tank for storage purpose not shown in the drawings via an expansion valve **33** provided in a line **L11**. The material gas subjected to the liquefaction step acquires a temperature of -162 degrees Celsius and a pressure of about 120 kPaA in the downstream end of the expansion valve **33**.

[0111] The material gas flowing through the liquefaction unit **21** is cooled by a refrigeration cycle using mixed refrigerants. In the illustrated embodiment, the mixed refrigerants may each contain nitrogen in addition to a mixture of hydrocarbons including methane, ethane and propane, but may also have other per se known compositions as long as the required cooling capability can be achieved.

[0112] In the liquefaction unit **21**, a high pressure (HP) mixed refrigerant (MR) is supplied to a refrigerant separator **41** via a line **L12**. The mixed refrigerant which makes up the liquid phase component in the refrigerant separator **41** is introduced into the liquefaction unit **21** via a line **L13**, and then flows upward in the liquefaction unit **21** through the piping systems **42a** and **42b** positioned in the warm regions **Z1a** and **Z1b**, respectively, and the piping system **43** positioned in the intermediate region **Z2**. The mixed refrigerant is then expanded in an expansion valve **44** provided in a line **L14**, and is partly flash vaporized.

[0113] After passing through the expansion valve **44**, the mixed refrigerant is ejected downward (so as to oppose the flow of the material gas in the liquefaction unit **21**) from a spray header **45** provided in an upper part of the intermediate region **Z2**. The mixed refrigerant ejected from the spray header **45** flows downward while exchanging heat with an intermediate tube bundle formed by the piping systems **31**, **43** and **52** (the last piping system will be discussed hereinafter) positioned in the intermediate region **Z2**, and a lower tube bundle formed by the piping systems **22a**, **22b**, **30**, **42a**, **42b**, **51a** and **51b** (the last two piping systems will be discussed hereinafter) positioned in the warm region **Z1**.

[0114] The mixed refrigerant that makes up the gas phase of the refrigerant separator **41** is introduced into the liquefaction unit **21** via a line **L15**, and then flows upward in the liquefaction unit **21** by flowing through the piping systems **51a** and **51b** positioned in the warm regions **Z1a** and **Z1b**, the piping system **52** in the intermediate region **Z2** and the piping system **53** positioned in the cold region **Z3**. The mixed refrigerant is then expanded in an expansion valve **54** provided in a line **L16**, and is partly flash vaporized.

[0115] The mixed refrigerant that has passed through the expansion valve **54** is already cooled to a temperature below the boiling point of methane (about -167 degrees Celsius in this case), and is expelled downward from a spray header **55** positioned in an upper part of the cold region **Z3** (or flows in opposite direction to the flow of the material gas in the liquefaction unit **21**). The mixed refrigerant ejected from the spray header **55** flows downward while exchanging heat with an upper tube bundle formed by the piping systems **32** and **53** positioned in the cold region **Z3**, and after mixing with the mixed refrigerant ejected from the spray header **45** located below, flows downward while exchanging heat with the intermediate tube bundle formed by the piping systems **31**, **43** and **52** positioned in the intermediate region **Z2**, and the lower tube bundle formed by the piping systems **22a**, **22b**, **30**, **42a**, **42b**, **51a** and **51b** positioned in the warm region **Z1**.

[0116] The mixed refrigerant ejected from the spray headers **45** and **55** is finally expelled via a line **L17** connected to the bottom end of the liquefaction unit **21** as low pressure (LP) mixed refrigerant (MP) gas. The facilities for the mixed refrigerant provided in the liquefaction unit **21** (such as the refrigerant separator **41**) form a part of a per se known refrigeration cycle for the mixed refrigerant, and the mixed refrigerant put out to the line **L17** is recirculated to the refrigerant separator **41** via the line **L12** after passing through compressors and condensers.

[0117] As discussed above, the material gas introduced into the liquefaction system **1** is effectively liquefied after being processed in the expansion step, the cooling step, the distillation step, the compression step and the liquefaction step. This liquefaction system can be applied, for instance, to a base load liquefaction plant for producing liquefied natural gas (LNG) mainly consisting of methane from the material gas mined from a gas field.

TABLE 1

No.	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)
vapor phase fraction	1.00	1.00	1.00	0.00	0.93	0.00	1.00	1.00	0.00
temperature [C.]	20.08	8.32	-42.58	177.19	-65.24	-65.24	-65.24	-50.99	-161.55
pressure [kPa]	5830.00	4850.00	4700.00	4705.00	4400.00	4400.00	4400.00	5483.00	120.00
molar flow rate [kgmole/h]	42000	42000	45020	313	45020	3334	41686	41686	41700
mass flow rate [kg/h]	719619	719619	783504	19764	783504	83548	699948	699948	698733
molar fraction									
nitrogen	0.008199590			0.000033626					0.008260844
methane	0.949952502			0.043508871					0.956667221
ethane	0.024998750			0.032339550					0.024931118
propane	0.009999500			0.143654595					0.009078200
butane	0.001999900			0.165149865					0.000793571
n-butane	0.001999900			0.232835468					0.000268518
i-pentane	0.000499975			0.066891831					0.000001710
n-pentane	0.000499975			0.067093928					0.000000817
n-hexane	0.000599970			0.080591893					0.000000000
benzene	0.000499975			0.067159786					0.000000000
toluene	0.000099995			0.013432078					0.000000000
p-xylene	0.000049998			0.006716040					0.000000000
n-heptane	0.000499975			0.067160391					0.000000000
n-octane	0.000099995			0.013432079					0.000000000

(First and Second Examples for Comparison)

[0118] FIGS. 2 and 3 are diagrams showing liquefaction process flows in conventional systems for the liquefaction of natural gas given as a first and a second example for comparison with the first embodiment of the present invention. In the conventional liquefaction systems **101** and **201** for natural gas, the parts corresponding to those of the liquefaction system of the first embodiment are denoted with like numerals. Tables 2 and 3 show the temperature, pressure, flow rate and molar fractions of the material gas in the liquefaction systems of the first and second examples for comparison, respectively. It should be noted that the liquefaction system **201** of the second example for comparison is based on the prior art disclosed in Patent Document 1 (U.S. Pat. No. 4,065,278).

[0119] As shown in FIG. 2, the liquefaction system **101** of the first example for comparison is not provided with the first expander **3** and the first compressor **4** used in the liquefaction system **1** of the first embodiment, and the material gas expelled from the water removal unit **2** is

forwarded to a cooler **110** via a line **L101**. A cooler unit is formed by connecting a cooler **11** and a cooler **12** to the downstream end of the cooler **110** in a serial connection so that the material gas is sequentially cooled by exchanging heat in the three coolers **110**, **11** and **12** which use a high pressure (HP), a medium pressure (MP) and a low pressure (LP) propane refrigerant, respectively. The material gas expelled from the cooler **12** in the downstream end has a temperature of about -34.5 degrees Celsius and a pressure of about 5,680 kPaA. The material gas is then depressurized by an expansion in an expansion valve **113** in a line **L4**, and is then introduced into a distillation unit **15**.

[0120] In the liquefaction system **101**, the material gas forming a gas phase component in the first gas-liquid separation vessel **23** and essentially consisting of methane is introduced into the piping system **31** positioned in the intermediate region **Z2** of the liquefaction unit **21** via a line **L102**. The material gas that is put out from the first gas-liquid separation vessel **23** to a line **L12** has a temperature of about -65.3 degrees Celsius and a pressure of about 4,400 kPaA.

TABLE 2

	No.							
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)
vapor phase fraction	1.00	0.99	1.00	0.00	0.93	0.00	1.00	0.00
temperature [C.]	20.08	-34.50	-42.58	176.73	-65.25	-65.25	-65.25	-161.56
pressure [kPa]	5830.00	5680.00	4700.00	4705.00	4400.00	4400.00	4400.00	120.00
molar flow rate [kgmole/h]	42000	42000	45020	314	45020	3334	41686	41700
mass flow rate [kg/h]	719619	719619	783488	19624	783454	83495	699951	696348
molar fraction								
nitrogen	0.008199590			0.000072318				0.008260784
methane	0.949952502			0.064051796				0.956622861
ethane	0.024998750			0.031841875				0.024947225
propane	0.009999500			0.129428030				0.009100267
butane	0.001999900			0.161816482				0.000796567
n-butane	0.001999900			0.231738008				0.000270095
i-pentane	0.000499975			0.066667173				0.000001771
n-pentane	0.000499975			0.066846201				0.000000423
n-hexane	0.000599970			0.080282498				0.000000003
benzene	0.000499975			0.066901980				0.000000003
toluene	0.000099995			0.013380485				0.000000000

TABLE 2-continued

	No.							
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)
p-xylene	0.000049998			0.006690243				0.000000000
n-heptane	0.000499975			0.066902427				0.000000000
n-octane	0.000099995			0.013380486				0.000000000

② indicates text missing or illegible when filed

[0121] As shown in FIG. 3, the liquefaction system 201 of the second example for comparison is an improvement of the liquefaction system 101 of the first example for comparison, and is provided with a first expander 3 and a first compressor 4. However, as opposed to the first expander 3 used in the liquefaction system 1 of the first embodiment, the expander 3 is positioned on the downstream side of the cooling unit (consisting the three coolers 110, 11 and 12 in this case). In the liquefaction system 201, the material gas expelled from the cooler 12 is forwarded to a separator 213 to be separated into gas and liquid components. The material gas that forms the gas phase component in the separator 213 is forwarded to the expander 3 to be expanded therein, and is then forwarded to the distillation unit 15 via a line L204. The part of the material gas that forms the liquid component in the separator 213 is put out to a line L205 provided with an expansion valve 214. The liquid that has been expanded in the expansion valve 214 is then forwarded to the distillation unit 15 via the line L204 along with the material gas from the expander 3.

[0122] The liquefaction system 201 is similar to that of the first embodiment as far as the part thereof downstream of the distillation unit 15 is concerned, and the material gas that has been put out to the line L10 by the compressor 4 has a temperature of about -54.7 degrees Celsius and a pressure of about 5,120 kPaA.

[0123] As can be appreciated by comparing the first and second examples for comparison with the present invention, the liquefaction system 1 according to the present invention allows a greater power to be produced by expanding material gas of higher temperature and higher pressure because the first expander 3 is positioned on the upstream side of the first cooling unit 11, 12, as compared to the liquefaction system 201 of the second example which has the expander 3 positioned on the downstream side of the cooling unit 110, 11, 12. As a result, the first compressor 4 can be driven with an increased power (or the outlet pressure of the first compressor 4 can be increased) so that the pressure of the material gas introduced into the liquefaction unit 21 can be increased, and the efficiency of the liquefaction process in the liquefaction unit 21 can be advantageously increased.

[0124] The liquefaction system 1 of the illustrated embodiment provides an additional advantage of reducing the required cooling capacity of the cooling unit (thereby allowing the cooler 110 in the second example for comparison to be omitted) because the temperature of the material gas is reduced by the expansion of the material gas in the first expander 3 owing to the positioning of the first expander 3 on the upstream side of the first cooling unit 11, 12. In the liquefaction system 1 of the illustrated embodiment, the

TABLE 3

	No.								
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)
vapor phase	1.00	1.00	1.00	0.00	0.94	0.00	1.00	1.00	0.00
faction									
temperature	20.08	-45.36	-44.83	208.13	-64.56	-64.56	-64.56	-54.74	-161.59
[C.]									
pressure [kPa]	5830.00	4705.00	4700.00	4705.00	4400.00	4400.00	4400.00	5120.00	120.00
molar flow	42000	41783	44200	302	44200	2500	41700	41700	41700
rate [kg②]									
mass flow	719619	709009	764342	19107	764342	63861	700471	700471	694674
rate [kg②]									
molar fraction									
nitrogen	0.008199590			0.000051871					0.008259333
methane	0.949952502			0.053398407					0.956509212
ethane	0.024998750			0.032075932					0.024927984
propane	0.009999500			0.133750785					0.009066826
butane	0.001999900			0.153843084					0.000893180
n-butane	0.001999900			0.230805233					0.000340430
i-pentane	0.000499975			0.069219794					0.000002448
n-pentane	0.000499975			0.069480324					0.000000589
n-hexane	0.000599970			0.083472642					0.000000000
benzene	0.000499975			0.069560398					0.000000000
toluene	0.000099995			0.013912204					0.000000000
p-xylene	0.000049998			0.006956102					0.000000000
n-heptane	0.000499975			0.069561020					0.000000000
n-octane	0.000099995			0.013912205					0.000000000

② indicates text missing or illegible when filed

gas-liquid separation vessel (separator **213**) for removing the condensate of the material gas placed between the cooling unit and the expander **3** may be omitted.

First Modification of the First Embodiment

[0125] FIG. 4 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a first modification of the first embodiment. In the liquefaction system illustrated in FIG. 4, the parts corresponding to those of the liquefaction system **1** of the first embodiment are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0126] In the liquefaction system of the first embodiment, a cascade refrigeration system using methane and ethylene for refrigerants is employed. The main heat exchanger is formed by a methane heat exchanger **21a** and an ethylene heat exchanger **21b** each consisting of a plate-fin type heat exchanger, instead of the spool-wound heat exchanger (liquefaction unit **21**) of the first embodiment.

[0127] The methane heat exchanger **21a** defines a warm region having a first heat transfer unit **61** that receives a high pressure (HP) methane refrigerant (C1R), an intermediate region having a second heat transfer unit **62** that receives a medium pressure (MP) methane refrigerant and a cold region having a third heat transfer unit **63** that receives a low pressure (LP) methane refrigerant.

[0128] The ethylene heat exchanger **21b** defines a warm region having a fourth heat transfer unit **64** that receives a high pressure (HP) ethylene refrigerant (C2R), an intermediate region having a fifth heat transfer unit **65** that receives a medium pressure (MP) ethylene refrigerant and a cold region having a sixth heat transfer unit **66** that receives a low pressure (LP) ethylene refrigerant.

[0129] The material gas that is separated as the top fraction in the distillation unit **15** is introduced into the liquefaction unit **21** via the line L6, and is cooled by a seventh heat transfer unit **22** positioned over the warm region and the intermediate region in the ethylene heat exchanger **21b**. The material gas compressed by the first compressor **4** is forwarded to the ethylene heat exchanger **21b** via the line L10. The material gas that flows the line L10 is introduced into an eighth heat transfer unit **67** positioned over the intermediate region and the cold region of the ethylene heat exchanger **21b** in two stages. The material gas expelled from the ethylene heat exchanger **21b** is introduced into a ninth heat transfer unit **68** extending from the warm region to the cold region of the ethane heat exchanger **21a** to be cooled in the warm region, the intermediate region and the cold region in three stages.

[0130] In the liquefaction system **1** of the first modification of the first embodiment of the present invention, an advantage in the facility of changing the point of connecting the line L10 to the main heat exchanger (the point of introducing the material gas into the ethylene heat exchanger **21b**) can be gained owing to the use of the plate-fin heat exchanger as the main heat exchanger. Therefore, even when the temperature level of the material gas flowing through the line L10 rises along with the pressure thereof, by changing the point of introducing the material gas into the heat exchanger depending on the temperature level of the material gas (or by bringing the temperature of the material close to the temperature at the point of introduction into the heat

exchanger), the thermal load on the heat exchanger can be reduced, and the efficiency of the liquefaction process can be increased.

Second, Third and Fourth Modifications of the First Embodiment

[0131] FIGS. 5, 6 and 7 are diagrams showing liquefaction process flows in systems for the liquefaction of natural gas given as a second, third and fourth modifications of the first embodiment, respectively. In the liquefaction systems illustrated in FIGS. 5, 6 and 7, the parts corresponding to those of the liquefaction system **1** of the first embodiment (as well as the other modifications) are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0132] As shown in FIG. 5, in the liquefaction system **1** of the second modification, a heat exchanger **69** is provided between the line L4 and the line L9. Thus, the material gas that is separated in the first gas-liquid separation vessel **23** as the gas phase component and flows through the line L9 is heated by exchanging heat with the material gas flowing from the cooling unit **12** to the distillation unit **15** via the line L4, before being introduced into the first compressor **4**. The material gas compressed by the first compressor **4** is introduced into the liquefaction unit **21** via the line L10. The downstream end of the line L10 is connected to a piping system **30** positioned in the warm region Z1 demonstrating the highest temperature in the liquefaction unit **21**. The piping system **30** forms a tube bundle that is positioned in the warm region Z1 jointly with a piping system **22** into which the top fraction of the distillation unit **15** is introduced, and a piping system **42** and a piping system **51** through which a mixed refrigerant flows.

[0133] Owing to this arrangement, in the second modification of the first embodiment, even when the temperature level of the material gas that is introduced into the liquefaction unit **21** via the line L10 should be lower than an appropriate range, the temperature of the material gas can be raised to an appropriate level by exchanging heat in the heat exchanger **69**. In other words, in the second modification of the first embodiment, the temperature of the material gas in the line L10 after the compression can be brought close to the temperature at the point of introduction (piping system **30**) in the liquefaction unit **21** (preferably with a deviation of less than 10 degrees Celsius) so that the thermal load on the liquefaction unit **21** can be reduced (or the generation of thermal stress can be minimized).

[0134] The arrangement of the heat exchanger **69** in the second modification can be freely changed as long as the temperature of the material gas in the line L10 after the compression can be brought close to the temperature at the introduction point of the liquefaction unit **21**. For instance, in the liquefaction system **1** of the third modification shown in FIG. 6, the heat exchanger **69** is provided between the line L4 and the line L10. The material gas compressed by the first compressor **4** and flowing through the line L10 is cooled by exchanging heat with the material gas flowing through the line L4 before being introduced into the liquefaction unit **21**. In the third modification, because the material gas heated by the heat exchanger **69** is introduced into the liquefaction unit **21** without the intervention of a device such as the first compressor **4**, the temperature of the material gas that is introduced into the liquefaction unit **1** can be controlled with ease.

[0135] As shown in FIG. 7, in the liquefaction system of the fourth modification, the heat exchanger 69 is provided between the line L4 and the line L6. Therefore, the material gas that is separated as a top fraction from the distillation unit 15 and flows through the line L6 is heated by exchanging heat with the material gas flowing through the line L4, before being introduced into the liquefaction unit 21 (the piping system 22). In particular, in the fourth modification, even when the material gas consists of natural gas (lean gas) containing a relatively low level of heavier components (higher hydrocarbons) as shown in Table 1, and the temperature of the material gas flowing through the line L6 following the distillation step may fall below an appropriate range, the temperature of the material gas can be raised to an appropriate level by exchanging heat in the heat exchanger 69.

Fifth Modification of the First Embodiment

[0136] FIG. 8 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a fifth modification of the first embodiment. In the liquefaction system illustrated in FIG. 8, the parts corresponding to those of the liquefaction system 1 of the first embodiment (including the modifications thereof) are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0137] The fifth modification is similar to the fourth modification, but further includes a heat exchanger 79 provided between the line L9 and the line L10. A fifth cooler 80 using a low pressure (LP) propane refrigerant (C3R) is further provided in the line L10. As a result, the material gas expelled from the first compressor 4 is cooled by exchanging heat with the material gas flowing through the line L9 before being introduced into the liquefaction unit 21. The downstream end of the line L10 is connected to a piping system 31 positioned in the intermediate region Z2.

[0138] In the fifth modification, the material gas expelled from the first compressor 4 can be introduced into the intermediate region Z2. Therefore, the tube bundle in the warm region Z1 can be formed by the three piping systems 22, 42 and 51, and the tube bundle in the intermediate region Z2 can be formed by the three piping systems 31, 43 and 52. As a result, in the fifth modification, when the liquefaction unit 21 is formed by using a spool-wound heat exchanger, the arrangement of the piping systems in the warm region Z1 and the intermediate region Z2 can be optimized (by uniformly spreading the piping systems among the different regions) as compared to the arrangement of the fourth modification so that the size of the liquefaction unit 21 is prevented from becoming excessively great. The fifth cooler 80 uses a propane refrigerant similarly to the first and second coolers 11 and 12 in the illustrated embodiment, by may also use other forms of air-cooled or water-cooled coolers.

Sixth Modification of the First Embodiment

[0139] FIG. 9 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as

a sixth modification of the first embodiment of the present invention. Table 4 shows the temperature, the pressure, the flow rate and the molar composition of the natural gas that is to be liquefied at each of various points in the liquefaction system of the sixth modification by way of an example. Table 5 shows the temperature, the pressure, the flow rate and the composition of the refrigerant in the refrigeration cycle of the mixed refrigerant used in the liquefaction system by way of an example. In the liquefaction system illustrated in FIG. 9, the parts corresponding to those of the liquefaction system 1 of the first embodiment (including the modifications thereof) are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0140] As shown in FIG. 9, the liquefaction system 1 of the sixth modification is similar to those of the second to the fourth modifications except for the difference in the material gas composition and the presence (or the absence) of the heat exchanger 69. The line L10 in this case is connected to the piping system 31 positioned in the intermediate region Z2 of the liquefaction unit 21. FIG. 9 also shows the structure of a refrigeration cycle system 70 using mixed refrigerants provided in the liquefaction system 1. The material gas in this case consists of natural gas (rich gas) having a relatively high levels of heavier contents (higher hydrocarbons) as shown in Table 4. By appropriately adjusting the expansion of the material gas in the first expander 3, the top fraction of the distillation unit 15 has a relatively low pressure (about 3,300 kPa) as compared with the first embodiment. As a result, in comparison with the liquefaction process of the lean gas such as the one discussed in conjunction with the first embodiment, the natural gas liquid can be recovered at a relatively high efficiency (about 89% of propane and about 100% of butane, for instance) via the line L5 connected to the bottom end of the distillation unit 15.

[0141] In the refrigeration cycle system 70, the mixed refrigerant of a relatively low pressure (about 320 kPa) expelled from the liquefaction unit 21 via the line L17 is compressed (first stage) by a first refrigerant compressor 17, cooled by a first intercooler 27, compressed (second stage) by a second refrigerant compressor 18, cooled by a second intercooler 28, compressed (third stage) by a third refrigerant compressor 19, and cooled by a third intercooler 29. The mixed refrigerant is then further cooled by a series of coolers including the first to fourth refrigerant coolers 34 to 37, and is introduced into a refrigerant separator 41 via the line L12. The first to fourth refrigerant coolers 34 to 37 cool the mixed refrigerant by stages by exchanging heat with the super high pressure (HHP), high pressure (HP), medium pressure (MP) and low pressure (LP) propane refrigerants.

[0142] As discussed above, the refrigeration cycle system 70 is provided with propane pre-cooling facilities (not shown in the drawings) for cooling the material gas before being introduced into the liquefaction unit 21, and a propane refrigerant is used for this purpose. Such a refrigeration cycle system 70 can also be applied to the other embodiments (including the modifications thereof).

TABLE 4

	No.				
	(i)	(ii)	(iii)	(iv)	(v)
vapor phase fraction	1.00	0.97	1.00	0.00	0.86
temperature [C.]	20.0	-15.2	-49.3	101.7	-71.6
pressure [kPa]	7000	3470	3300	3310	3000

TABLE 4-continued

molar flow rate [kgmole/h]	42000	42000	45704	2601	45704
mass flow rate [kg/h]	803679	803679	822638	134105	822638
molar fraction					
nitrogen	0.001000	0.001000	0.000940	0.000000	0.000940
methane	0.877900	0.877900	0.880344	0.001278	0.880344
ethane	0.060900	0.060900	0.098820	0.084051	0.098820
propane	0.033600	0.033600	0.019856	0.485204	0.019856
butane	0.006500	0.006500	0.000034	0.104921	0.000034
n-butane	0.011500	0.011500	0.000007	0.185684	0.000007
i-pentane	0.003400	0.003400	0.000000	0.054899	0.000000
n-pentane	0.002100	0.002100	0.000000	0.033908	0.000000
n-hexane	0.003100	0.003100	0.000000	0.050055	0.000000
benzene	0.000000	0.000000	0.000000	0.000000	0.000000
toluene	0.000000	0.000000	0.000000	0.000000	0.000000
p-xylene	0.000000	0.000000	0.000000	0.000000	0.000000
n-heptane	0.000000	0.000000	0.000000	0.000000	0.000000
n-octane	0.000000	0.000000	0.000000	0.000000	0.000000

	No.			
	(vi)	(vii)	(viii)	(ix)
vapor phase fraction	0.00	1.00	1.00	0.00
temperature [C.]	-71.6	-71.6	-27.1	-159.0
pressure [kPa]	3000	3000	5752	120
molar flow rate [kgmole/h]	6306	39399	39399	39399
mass flow rate [kg/h]	153064	669574	669574	669574
molar fraction				
nitrogen	0.000152	0.001066	0.001066	0.001066
methane	0.533997	0.935775	0.935775	0.935775
ethane	0.345301	0.059372	0.059372	0.059372
propane	0.120269	0.003785	0.003785	0.003785
butane	0.000231	0.000002	0.000002	0.000002
n-butane	0.000051	0.000000	0.000000	0.000000
i-pentane	0.000000	0.000000	0.000000	0.000000
n-pentane	0.000000	0.000000	0.000000	0.000000
n-hexane	0.000000	0.000000	0.000000	0.000000
benzene	0.000000	0.000000	0.000000	0.000000
toluene	0.000000	0.000000	0.000000	0.000000
p-xylene	0.000000	0.000000	0.000000	0.000000
n-heptane	0.000000	0.000000	0.000000	0.000000
n-octane	0.000000	0.000000	0.000000	0.000000

TABLE 5

	No.						
	(xi)	(xii)	(xiii)	(xiv)	(xv)	(xvi)	(xvii)
vapor phase fraction	0.29	1.00	0.00	0.00	0.00	0.00	1.00
temperature [C.]	-34.5	-34.5	-34.5	-135.0	-139.5	-160.9	-167.0
pressure [kPa]	5950	5950	5950	5020	365	4570	320
molar flow rate [kgmole/h]	64912	18845	46067	46067	46067	18845	64912
mass flow rate[kg/h]	1688828	400927	1287901	1287901	1287901	400927	1688828
molar fraction							
nitrogen	0.095000	0.208834	0.048433				0.095000
methane	0.445000	0.625994	0.370959				0.445000
ethane	0.290000	0.135564	0.353177				0.290000
propane	0.170000	0.029607	0.227432				0.170000
butane	0.000000	0.000000	0.000000				0.000000
n-butane	0.000000	0.000000	0.000000				0.000000
i-pentane	0.000000	0.000000	0.000000				0.000000
n-pentane	0.000000	0.000000	0.000000				0.000000
n-hexane	0.000000	0.000000	0.000000				0.000000
benzene	0.000000	0.000000	0.000000				0.000000
toluene	0.000000	0.000000	0.000000				0.000000

TABLE 5-continued

	No.						
	(xi)	(xii)	(xiii)	(xiv)	(xv)	(xvi)	(xvii)
p-xylene	0.000000	0.000000	0.000000				0.000000
n-heptane	0.000000	0.000000	0.000000				0.000000
n-octane	0.000000	0.000000	0.000000				0.000000

Seventh Modification of the First Embodiment

[0143] FIG. 10 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a seventh modification of the first embodiment of the present invention. Table 6 shows the temperature, the pressure, the flow rate and the molar composition of the natural gas that is to be liquefied at each of various points in the liquefaction system of the seventh modification by way of an example. In the liquefaction system illustrated in FIG. 10, the parts corresponding to those of the liquefaction system 1 of the first embodiment (including the modifications thereof) are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0144] In the seventh modification, rich gas is used as the material gas similarly as in the sixth modification, and this modification is advantageous when the material gas is composed such that the critical pressure thereof is relatively high. In the liquefaction system 1, a third cooler 86 using a low pressure (LP) propane refrigerant (C3R) is provided in a line L6 connecting the distillation unit 15 to the first gas-liquid separation vessel 23, and a second cooler 85 using a similar low pressure propane refrigerant is provided in a

line L10 connecting the first compressor 4 to the liquefaction unit 21. Thus, the material gas expelled from the distillation unit 15 to the line L6 is cooled by the third cooler 86, and is introduced into the first gas-liquid separation vessel 23. Therefore, in the seventh modification, the material gas to be introduced into the first gas-liquid separation vessel 23 is not required to be cooled by the liquefaction unit 21 (piping system 22) as opposed to the other modifications such as the sixth modification so that the load on the liquefaction process of the liquefaction unit 21 can be reduced.

[0145] The material gas that is expelled from the first compressor 4 to the line L10 is cooled by the second cooler 85, and is then introduced into the liquefaction unit 21. In this case, the downstream end of the line L10 is connected to the piping system 30 which is positioned in the warm region Z1 or the warmest part of the liquefaction unit 21. Thus, in the seventh modification, even when the temperature level of the material gas should exceed an appropriate range owing to the compression of the material gas, the cooling in the second cooler 85 can bring the temperature of the material gas close to the temperature level of the warm region Z1 of the liquefaction unit 21 so that the thermal load (thermal stresses) on the liquefaction unit 21 can be reduced.

TABLE 6

	No.				
	(i)	(ii)	(iii)	(iv)	(v)
vapor phase fraction	1.00	1.00	1.00	0.00	0.96
temperature [C.]	20.0	10.3	-19.6	79.8	-19.6
pressure [kPa]	8000	6830	6670	6680	6670
molar flow rate [kgm ³ /h]	42000	42000	41945	1822	41945
mass flow rate [kg/h]	807998	807998	775992	83599	775992
molar fraction					
nitrogen	0.007000	0.007000	0.007086	0.000025	0.007086
methane	0.871400	0.871400	0.886689	0.208770	0.886689
ethane	0.060900	0.060900	0.060265	0.147847	0.060265
propane	0.033600	0.033600	0.030817	0.220181	0.030817
butane	0.006500	0.006500	0.005176	0.073071	0.005176
n-butane	0.011500	0.011500	0.008181	0.156499	0.008181
i-pentane	0.003400	0.003400	0.001290	0.066143	0.001290
n-pentane	0.002100	0.002100	0.000472	0.044574	0.000472
n-hexane	0.003100	0.003100	0.000021	0.071376	0.000021
benzene	0.000500	0.000500	0.000003	0.011515	0.000003
toluene	0.000000	0.000000	0.000000	0.000000	0.000000
p-xylene	0.000000	0.000000	0.000000	0.000000	0.000000
n-heptane	0.000000	0.000000	0.000000	0.000000	0.000000
n-octane	0.000000	0.000000	0.000000	0.000000	0.000000

	No.			
	(vi)	(vii)	(viii)	(ix)
vapor phase fraction	0.00	1.00	1.00	0.00
temperature [C.]	-32.6	-32.6	-34.5	-160.9
pressure [kPa]	6600	6600	7601	120
molar flow rate [kgm ³ /h]	1767	40178	40178	40178
mass flow rate [kg/h]	51592	724400	724400	724400

TABLE 6-continued

molar fraction				
nitrogen	0.001845	0.007316	0.007316	0.007316
methane	0.551125	0.901446	0.901446	0.901446
ethane	0.135468	0.056958	0.056958	0.056958
propane	0.159919	0.025140	0.025140	0.025140
butane	0.043703	0.003481	0.003481	0.003481
n-butane	0.082213	0.004925	0.004925	0.004925
i-pentane	0.018010	0.000555	0.000555	0.000555
n-pentane	0.007251	0.000174	0.000174	0.000174
n-hexane	0.000412	0.000004	0.000004	0.000004
benzene	0.000054	0.000001	0.000001	0.000001
toluene	0.000000	0.000000	0.000000	0.000000
p-xylene	0.000000	0.000000	0.000000	0.000000
n-heptane	0.000000	0.000000	0.000000	0.000000
n-octane	0.000000	0.000000	0.000000	0.000000

② indicates text missing or illegible when filed

Eighth Modification of the First Embodiment

[0146] FIG. 33 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as an eighth modification of the first embodiment of the present invention. In the liquefaction system illustrated in FIG. 33, the parts corresponding to those of the liquefaction system 1 of the first embodiment (including the modifications thereof) are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0147] The eighth modification is similar to the fifth modification discussed above, but the fifth cooler 80 of the fifth modification is omitted, and a heat exchanger 100 is added between the line L6 leading from the distillation unit 15 and the line L10 leading from the first compressor 4. As a result, the material gas expelled from the first compressor 4 to the line L10 is cooled by the material gas (top fraction) expelled from the distillation unit 15 to the line L6, instead of being cooled by the fifth cooler 80, and is introduced into a heat exchanger 79 similarly to that of the fifth modification. Meanwhile, the material gas expelled from the distillation unit 15 is introduced into the liquefaction unit 21 via the line L6 following the heat exchange, and is then cooled by the piping system 22. Owing to this arrangement, in the eighth modification, the cooling of the material gas by the fifth cooler 80 as in the fifth embodiment may be augmented or replaced by the heat exchange in the heat exchanger 100. In the eighth embodiment, the heat exchanger 69 that was used in the fifth embodiment is omitted, but it is also possible to arrange such that the material gas expelled from the distillation unit 15 to the line L6 is introduced into the heat exchanger 100 via the heat exchanger 69.

Second Embodiment

[0148] FIG. 11 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a second embodiment of the present invention. Table 7 shows the temperature, the pressure, the flow rate and the molar composition of the natural gas that is to be liquefied at each of various points in the liquefaction system of the second embodiment by way of an example. In the liquefaction system illustrated in FIG. 11, the parts corresponding to those of the liquefaction system 1 of the first embodiment are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0149] The liquefaction system 1 of the second embodiment further includes a fourth compressor 71 for gas supply and a fourth cooler 72 on the upstream end of the line L1 for

supplying the material gas to the water removal unit 2. In this liquefaction system 1, the material gas supplied from a line L18 is compressed by the fourth compressor 71 for gas supply, and cooled by the fourth cooler 72 connected to the downstream end thereof before being supplied to the water removal unit 2.

[0150] In this liquefaction system 1 of the second embodiment, even when the pressure of the material gas that is supplied to the liquefaction system 1 is relatively low, the material gas can be compressed to a desired pressure by the fourth compressor 71 for gas supply so that the material gas that is supplied from the first compressor 4 to the liquefaction unit 21 can be maintained at a relatively high pressure level (about 6,800 kPaA in this case). This liquefaction system 1 is particularly suitable for processing material gas from a source of a relatively low pressure such as shale gas.

[0151] Also, because the liquefaction system 1 of the second embodiment can maintain the temperature of the material gas that is supplied from the first compressor 4 to the liquefaction unit 21 at a relatively high level, owing to the presence of the fourth compressor 71 for gas supply, the line L10 may be connected to the piping system 30 positioned in a warm part or the warm region Z1 of the liquefaction unit 21 (the point of introducing the mixed refrigerant having a substantially same temperature level as the material gas that is introduced into the liquefaction unit 21). Thereafter, the material gas is caused to flow from the piping system 30 to the piping system 31 positioned in the intermediate region Z2 and thence to the piping system 32 positioned in the cold region Z3 to be liquefied and super cooled.

[0152] Thus, in the liquefaction system 1 of the second embodiment, even when the temperature of the material gas that is introduced into the liquefaction unit 21 should rise, because the material gas is introduced into the warm region Z1 (high temperature side) of the liquefaction unit 21 having a similar temperature level, the thermal load (thermal stresses) on the liquefaction unit 21 can be reduced, and the efficiency of the liquefaction process can be increased. The liquefaction system 1 can be configured such that the material gas is introduced into the warm region Z1 of the liquefaction unit 21, without regard to the presence of the fourth compressor 71 for gas supply, depending on the pressure level of the material gas. If the pressure of the material gas is so high that the temperature of the material gas is higher than the warm region Z1 (high temperature side) of the liquefaction unit 21, the load on the liquefaction unit 21 can be reduced by providing the second cooler 85 similarly as in the embodiment illustrated in FIG. 10.

TABLE 7

	No.			
	(i)	(ii)	(iii)	(iv)
vapor phase fraction	1.00	0.99926814	0.99999155	0.00
temperature [C.]	20.14	-4.64	-42.58	175.78
pressure [kPa]	7180.00	4850.00	4700.00	4705.00
molar flow rate [kgmole/h]	42000	42000	45020	312.584899
mass flow rate [kg②]	719619	719619	783495	19781
molar fraction				
nitrogen	0.008199590			0.000031631
methane	0.949952502			0.041864778
ethane	0.024998750			0.032036256
propane	0.009999500			0.144339655
butane	0.001999900			0.165884716
n-butane	0.001999900			0.233258825
i-pentane	0.000499975			0.066912683
n-pentane	0.000499975			0.067112604
n-hexane	0.000599970			0.080613490
benzene	0.000499975			0.067177784
toluene	0.000099995			0.013435677
p-xylene	0.000049998			0.006717839
n-heptane	0.000499975			0.067178385
n-octane	0.000099995			0.013435678

	No.				
	(v)	(vi)	(vii)	(viii)	(ix)
vapor phase fraction	0.926255	0.00	1.00	1.00	0.00
temperature [C.]	-65.19	-65.19	-65.19	-38.31	-161.55
pressure [kPa]	4400.00	4400.00	4400.00	6799.08	120.00
molar flow rate [kgmole/h]	45020	3320	41700	41700	41700
mass flow rate [kg②]	783495	83262	700225	698733	698733
molar fraction					
nitrogen					0.008252582
methane					0.956625333
ethane					0.024955530
propane					0.009098899
butane					0.000795603
n-butane					0.000269470
i-pentane					0.000001763
n-pentane					0.000000820
n-hexane					0.000000000
benzene					0.000000000
toluene					0.000000000
p-xylene					0.000000000
n-heptane					0.000000000
n-octane					0.000000000

② indicates text missing or illegible when filed

Third Embodiment

[0153] FIG. 12 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a third embodiment of the present invention. Table 8 shows the temperature, the pressure, the flow rate and the molar composition of the natural gas that is to be liquefied at each of various points in the liquefaction system of the third embodiment by way of an example. In the liquefaction system illustrated in FIG. 12, the parts corresponding to those of the liquefaction systems 1 of the first and second embodiments are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0154] The liquefaction system 1 of the third embodiment further includes a second compressor 75 for additional compression connected to the downstream end of the first

compressor 4 so that the material gas which has been compressed by the first compressor 4 is forwarded to the second compressor 75 via a line L10a, and after being further compressed (to about 7,000 kPaA in this case) in the second compressor 75, is introduced into the liquefaction unit 21 via a line L10b. The internal structure of the liquefaction unit 21 is similar to that of the second embodiment, and the line L10b is connected to a piping system 30 positioned in the warm region Z1 of the liquefaction unit 21. [0155] In the liquefaction system 1 of the third embodiment, because the second compressor 75 is added to the downstream end of the first compressor 4, the pressure of the material gas that is forwarded from the second compressor 75 to the liquefaction unit 21 via the line L10b can be increased even further (up to 7,000 to 10,000 kPaA, for instance) so that the efficiency of the liquefaction process can be increased even further.

TABLE 8

	No.				
	(i)	(ii)	(iii)	(iv)	(v)
vapor phase fraction	1.00	1.00	0.99998949	0.00	0.925944
temperature [C.]	20.08	8.32	-42.58	177.19	-65.24
pressure [kPa]	5830.00	4850.00	4700.00	4705.00	4400.00
molar flow rate [kgmole/h]	42000	42000	45020	312.6686486	45020
mass flow rate [kg②]	719619	719619	783504	19764	783504
molar fraction					
nitrogen	0.008199590			0.000033626	
methane	0.949952502			0.043508871	
ethane	0.024998750			0.032339550	
propane	0.009999500			0.143654595	
butane	0.001999900			0.165149865	
n-butane	0.001999900			0.232835468	
i-pentane	0.000499975			0.066891831	
n-pentane	0.000499975			0.067093928	
n-hexane	0.000599970			0.080591893	
benzene	0.000499975			0.067159786	
toluene	0.000099995			0.013432078	
p-xylene	0.000049998			0.006716040	
n-heptane	0.000499975			0.067160391	
n-octane	0.000099995			0.013432079	

	No.			
	(vi)	(vii)	(viii)	(ix)
vapor phase fraction	0.00	1.00	1.00	0.00
temperature [C.]	-65.24	-65.24	-34.55	-161.55
pressure [kPa]	4400.00	4400.00	7000.00	120.00
molar flow rate [kgmole/h]	3334	41686	41686	41700
mass flow rate [kg②]	83548	699948	699948	698733
molar fraction				
nitrogen				0.008260844
methane				0.956667221
ethane				0.024931118
propane				0.009076200
butane				0.000793571
n-butane				0.000268518
i-pentane				0.000001710
n-pentane				0.000000817
n-hexane				0.000000000
benzene				0.000000000
toluene				0.000000000
p-xylene				0.000000000
n-heptane				0.000000000
n-octane				0.000000000

② indicates text missing or illegible when filed

Modification of the Third Embodiment

[0156] FIG. 13 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a modification of the third embodiment of the present invention. In the liquefaction system illustrated in FIG. 13, the parts corresponding to those of the liquefaction system 1 of the first to the third embodiments are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0157] In the liquefaction system of this modification, the second compressor 75 is driven by an electric motor (first electric motor) 81, and the speed of the electric motor 81 is controlled by a controller 82 designed for variable frequency drive. The electric motor 81 receives an external supply of electric power. The speed of the electric motor 81 (or the operation of the second compressor 75) is controlled according to the pressure value detected by a pressure gauge 83

provided in the line L10b so that the pressure of the material gas that is introduced into the liquefaction unit 21 is maintained at a fixed value (or within a fixed range). As a result, the pressure of the material gas that is introduced into the liquefaction unit 21 can be increased by the second compressor 75 in a stable manner so that the temperature of the material gas is also maintained within an appropriate range, and the liquefaction process in the liquefaction unit 21 can be carried out in a both efficient and stable manner.

Fourth Embodiment

[0158] FIG. 14 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a fourth embodiment of the present invention. Table 9 shows the temperature, the pressure, the flow rate and the molar composition of the natural gas that is to be liquefied at each of various points in the liquefaction system of the

fourth embodiment by way of an example. In the liquefaction system illustrated in FIG. 14, the parts corresponding to those of the liquefaction system 1 of the first to third embodiments are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0159] The liquefaction system 1 of the fourth embodiment further includes a second cooler 85 using a low pressure (LP) propane refrigerant (C3R) provided on the downstream end of the second compressor 75 of the third embodiment shown in FIG. 12. The material gas that is expelled from the first compressor 4 to the line L10a is compressed by the second compressor 75, forwarded to the second cooler 85 to be cooled thereby, and introduced into the liquefaction unit 21 via a line L10c. The internal structure of the liquefaction unit 21 is similar to that of the third embodiment, and the line L10c is connected to a piping system 30 positioned in the warm region Z1 of the liquefaction unit 21.

[0160] In the liquefaction system 1 of the fourth embodiment, owing to the compression of the material gas by the second compressor 75, even when the temperature of the material gas should exceed an appropriate range, by cooling the material gas in the second cooler 85 provided downstream of the second compressor 75 by using a low pressure propane refrigerant, the temperature of the material gas can be brought close to the temperature level of the warm region Z1 of the liquefaction unit 21 so that the thermal load on the liquefaction unit 21 can be reduced, and the efficiency of the liquefaction process can be increased. If the second cooler 85 (using a propane refrigerant demonstrating a higher cooling capability than water or air) is used for the cooling of the material gas in the recycle operation at the time of the startup of the first compressor 4, an improved cooling (below 0 degrees Celsius) performance can be achieved.

TABLE 9

	No.				
	(i)	(ii)	(iii)	(iv)	(v)
vapor phase fraction	1.00	1.00	0.99998949	0.00	0.925944
temperature [C.]	20.08	8.32	-42.58	177.19	-65.24
pressure [kPa]	5830.00	4850.00	4700.00	4705.00	4400.00
molar flow rate [kgmole/h]	42000	42000	45020	312.6686486	45020
mass flow rate [kg②]	719619	719619	783504	19764	783504
molar fraction					
nitrogen	0.008199590			0.000033626	
methane	0.949952502			0.043508871	
ethane	0.024998750			0.032339550	
propane	0.009999500			0.143654595	
butane	0.001999900			0.165149865	
n-butane	0.001999900			0.232835468	
i-pentane	0.000499975			0.066891831	
n-pentane	0.000499975			0.067093928	
n-hexane	0.000599970			0.080591893	
benzene	0.000499975			0.067159786	
toluene	0.000099995			0.013432078	
p-xylene	0.000049998			0.006716040	
n-heptane	0.000499975			0.067160391	
n-octane	0.000099995			0.013432079	

	No.			
	(vi)	(vii)	(viii)	(ix)
vapor phase fraction	0.00	1.00	1.00	0.00
temperature [C.]	-65.24	-65.24	-34.50	-161.55
pressure [kPa]	4400.00	4400.00	8000.00	120.00
molar flow rate [kgmole/h]	3334	41686	41686	41700
mass flow rate [kg②]	83548	699948	699948	698733
molar fraction				
nitrogen				0.008260844
methane				0.956667221
ethane				0.024931118
propane				0.009076200
butane				0.000793571
n-butane				0.000268518
i-pentane				0.000001710
n-pentane				0.000000817
n-hexane				0.000000000
benzene				0.000000000
toluene				0.000000000
p-xylene				0.000000000
n-heptane				0.000000000
n-octane				0.000000000

② indicates text missing or illegible when filed

[0161] Table 10 compares the power requirements of the various compressors in the first to fourth embodiments, and the first and second examples for comparison. As shown in Table 10, the total power requirements and specific powers of the first to fourth embodiments are less than those of the first and second examples for comparison (prior art).

TABLE 10

	Example 1 for Comparison	Example 2 for Comparison	1st Embodiment	2nd Embodiment	3rd Embodiment	4th Embodiment
1st Compressor [kW]		2493	3616	7267	3616	3616
2nd Compressor [kW]					4402	7099
4th Compressor [kW]				7561		
Mixed Refrigerant Compressor [kW]	161680	155260	153620	150350	148940	143590
Propane Compressor [kW]	76651	74827	72247	68689	70756	72769
Total [kW]	238331	233057	225867	226600	224098	223458
LNG [t/h]	698.8	694.7	698.8	698.8	698.8	698.8
Specific Power [kW/t]	341	335	323	324	321	320

Fifth Embodiment

[0162] FIG. 15 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a fifth embodiment of the present invention. In the liquefaction system illustrated in FIG. 15, the parts corresponding to those of the liquefaction systems 1 of the first to fourth embodiments are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0163] In the liquefaction system 1 of the fifth embodiment, as opposed to the first to fourth embodiments, the first expander 3 and the first compressor 4 are not mechanically connected to each other, but are electrically connected to each other. The first expander 3 is connected to an electric generator 87 so that the power generated by the expander 3 is converted into electric power by the electric generator 87. The electric power generated by the electric generator 87 is supplied to an electric motor 84 for driving the first compressor 4. In other words, the power generated by the first expander 3 is used by the first compressor 4. The electric power supplied by the electric generator 87 may be at least a part of the electric power that is used for driving the electric motor 84, and when there is a shortage of electric power, the external power source may be used for augmenting the shortfall of the electric power.

[0164] In the liquefaction system 1 of the fifth embodiment, because the first expander 3 and the first compressor 4 are electrically connected to each other, the freedom in the mode of operation of the first expander 3 and the first compressor 4 at the time of startup and/or power-down can be increased (such that the first expander 3 and the first compressor 4 can be individually operated, for instance).

Sixth Embodiment

[0165] FIG. 16 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a sixth embodiment of the present invention. In the liquefaction system illustrated in FIG. 16, the parts corresponding to those of the liquefaction system 1 of the first to fifth embodiments are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0166] In the liquefaction system 1 of the sixth embodiment, rich gas containing 88 mol % of methane is used as the material gas (similarly to the modification of the sixth embodiment, and the seventh and eighth embodiments). In this liquefaction system, the material gas that is separated as a top fraction in the distillation unit 15 is directly introduced

into the first compressor 4 to be compressed thereby via a line L19. The material gas is then pre-cooled in the piping system 22 in the warm region Z1, and forwarded to a first gas-liquid separation vessel 23 via a line L21.

[0167] The first gas-liquid separation vessel 23 separates a liquid phase component (condensate) of the material gas, and the hydrocarbons in liquid form forming the liquid phase component is recirculated to the distillation unit 15 via an expansion valve 89 provided in a line L22. Meanwhile, the material gas mainly consisting of methane and forming the liquid phase component in the first gas-liquid separation vessel 23 is forwarded to the piping system 31 in the liquefaction unit 21 via a line L23.

[0168] In the liquefaction system 1 of the sixth embodiment, because the first gas-liquid separation vessel 23 is provided on the downstream side of the first compressor 4, and the material gas expelled from the first compressor 4 is introduced into the first gas-liquid separation vessel 23 via the piping system 22 positioned in the warm region Z1, the temperature of the material gas can be brought close to the temperature level of the warm region Z1 of the liquefaction unit 21. Furthermore, because the material gas is cooled in the warm region Z1 (piping system 22) of the liquefaction unit 21, and the gas phase component expelled from the first gas-liquid separation vessel 23 is introduced into the intermediate region Z2 (piping system 31), the temperature of the material gas can be brought close to the temperature level of the intermediate region Z2 of the liquefaction unit 21 with ease. Also, because the material gas expelled from the first gas-liquid separation vessel 23 can be placed under pressure by the first compressor 4, the recirculation pump 24 provided in the recirculation line (line L21) extending from the first gas-liquid separation vessel 23 to the distillation unit 15 in some of the embodiments including the first embodiment can be omitted.

[0169] In the liquefaction of the material gas in the liquefaction unit 21, raising the outlet pressure of the compressor 4 (or increasing the pressure of the material gas that is introduced into the liquefaction unit 21) is advantageous. However, when the top fraction of the distillation unit 15 is cooled in the liquefaction unit 21, separated in the first gas-liquid separation vessel 23, and the separated gas phase component is compressed by the first compressor 4 before

being introduced into the liquefaction unit **21** as was the case with the first embodiment, because the temperature of the material gas is increased by the first compressor **4** preceding the liquefaction unit **21**, depending the conditions associated with the composition, pressure and feed rate of the material gas, the temperature level of the material gas may deviate from a suitable range for introduction into the liquefaction unit **21** so that the thermal load on the liquefaction unit **21** may become excessive. Such a problem can be resolved by changing the point of introducing the material gas into the liquefaction unit **21**, but when the main heat exchanger consists of a kind such as a spool-wound heat exchanger which does not allow the point of introduction to be changed with ease, it may not be the case. Thus, if the material gas separated as the top fraction in the distillation unit **15** is forwarded directly to the first compressor **4** via the line **L19** to be compressed, the material gas compressed by the first compressor **4** is cooled in the warm region **Z1** of the liquefaction unit **21**, the cooled material gas is separated in the first gas-liquid separation vessel **23**, and the separated gas phase component of the material gas is introduced into the intermediate region **Z2** (downstream of the warm region **Z1**) of the liquefaction unit **21**, as is the case with the present embodiment, the temperature of the material gas can be maintained within an appropriate range (or the temperature of the material gas can be brought close to the temperature level at the introduction point of the liquefaction unit **21**).

First Modification of the Sixth Embodiment

[0170] FIG. 17 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given

as a modification of the sixth embodiment of the present invention. Table 11 shows the temperature, the pressure, the flow rate and the molar composition of the natural gas that is to be liquefied at each of various points in the liquefaction system of the sixth embodiment by way of an example. In the liquefaction system illustrated in FIG. 17, the parts corresponding to those of the liquefaction system **1** of the sixth embodiment are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0171] In this liquefaction system **1** of this modification, the first cooler **11** used in the sixth embodiment shown in FIG. 16 is omitted, and a second cooler **85** using low pressure propane as the refrigerant is provided on the downstream side of the first compressor **4**. The material gas is forwarded from the first compressor **4** to the second cooler **85** to be cooled therein via a line **L20a**, and is forwarded to a piping system **22** positioned in the warm region **Z1** of the liquefaction unit **21** via a line **L20b** to be further cooled before being introduced into the first gas-liquid separation vessel **23** via a line **L21**.

[0172] In this liquefaction system of the first modification of the sixth embodiment, because the second cooler **85** is provided on the downstream side of the first compressor **4**, even when the temperature of the material gas expelled from the first compressor **4** is higher than the temperature in the warm region **Z1** of the liquefaction unit **21**, owing to the cooling action of the second cooler **85** applied to the material gas, the temperature of the material gas can be brought close to the temperature level of the warm region **Z1** of the liquefaction unit **21**.

TABLE 11

	No.								
	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)	(ix)
vapor phase	1.00	0.97	1.00	0.00	1.00	0.82	0.00	1.00	0.00
faction									
temper-	20.00	-15.21	-52.85	95.46	-18.62	-63.17	-63.17	-63.17	-159.04
ature [C.]									
pressure	7000.00	3470.10	3300.00	3310.00	5335.67	4985.67	4985.67	4985.67	120.00
[kPa]									
molar	42000	42000	48048.7985	2599.94689	48048.8	48048.8	8648.78	39400	39400.01475
flow rate									
[kgmole/h]									
mass flow	803679	803679	849289	132033	849289	849289	177669	671605	671605
rate [kg [Ⓢ]]									
molar									
fraction									
nitrogen	0.001000000			0.000000012					0.001066081
methane	0.877900000			0.002690816					0.935674952
ethane	0.060900000			0.136450252					0.055944425
propane	0.033600000			0.431375809					0.007299533
butane	0.006500000			0.104814783					0.000012789
n-butane	0.011500000			0.185742438					0.000002218
i-pentane	0.003400000			0.054924175					0.000000002
n-pentane	0.002100000			0.033923768					0.000000000
n-hexane	0.003100000			0.050077946					0.000000000
benzene	0.000000000			0.000000000					0.000000000
toluene	0.000000000			0.000000000					0.000000000
p-xylene	0.000000000			0.000000000					0.000000000
n-heptane	0.000000000			0.000000000					0.000000000
n-octane	0.000000000			0.000000000					0.000000000

Ⓢ indicates text missing or illegible when filed

Second and Third Modifications of the Sixth Embodiment

[0173] FIGS. 18 and 19 are diagrams showing liquefaction process flows in systems for the liquefaction of natural gas given as a second and a third modification of the sixth embodiment of the present invention, respectively. In the liquefaction systems illustrated in FIGS. 18 and 19, the parts corresponding to those of the liquefaction system 1 of the sixth embodiment (including other embodiments and modifications) are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0174] As shown in FIG. 18, the liquefaction system 1 of the second modification includes a heat exchanger 69 positioned between the line L4 and the line L19 so that the material gas that is separated as a top fraction in the distillation unit 15 and conducted through the line L19 is heated by exchanging heat with the material gas that flows through the line L4 from the cooler 12 to the distillation unit 15, and is then introduced into the first compressor 4. The material gas which has been compressed by the first compressor 4 is introduced into the liquefaction unit 21 via the line L20. The downstream end of the line L20 is connected to the piping system 22 positioned in the warm region Z1 or the warmest part of the liquefaction unit 21.

[0175] Owing to this arrangement, in the second modification, even when the temperature of the material gas introduced into the liquefaction unit 21 via the line L20 should fall below an appropriate temperature range, the temperature of the material gas can be raised to an appropriate level by the exchange of heat in the heat exchanger 69. In other words, the temperature of the material gas in the line L20 which has been compressed can be brought close to the temperature at the introduction point (piping system 22) in the liquefaction unit 21 so that the thermal load (thermal stresses) on the liquefaction unit 21 can be reduced.

[0176] As shown in FIG. 19, the liquefaction system 1 of the third modification includes a heat exchanger 69 positioned between the line L4 and the line L20 so that the material gas expelled from the first compressor 4 and conducted through the line L20 is heated by the exchange of heat with the material gas flowing through the line L4, and is then introduced into the piping system positioned in the warm region Z1 of the liquefaction unit 21. In the third modification, the material gas heated in the heat exchanger 69 is directly introduced into the liquefaction unit 21 without

the intervention of the first compressor 4 so that the temperature of the material gas that is introduced into the liquefaction unit 21 can be controlled with ease.

[0177] The positioning of the heat exchanger 69 in the second and third modifications of the sixth embodiment can be changed variously without departing from the spirit of the present invention as long as the temperature of the material gas in the line L20 following the compression can be brought close to the temperature at the introduction point of the liquefaction unit 21.

[0178] FIG. 20 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a fourth modification of the sixth embodiment of the present invention. Table 12 shows the temperature, the pressure, the flow rate and the molar composition of the natural gas that is to be liquefied at each of various points in the liquefaction system of the fourth modification by way of an example. In the liquefaction system illustrated in FIG. 20, the parts corresponding to those of the liquefaction system 1 of the sixth embodiment (including the other modifications) are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0179] The fourth modification is configured to be suitable when the material gas has a relatively low pressure, and the critical pressure thereof is relatively high owing to the composition of the material gas which may include nitrogen and heavier contents, as compared with the sixth embodiment. In the liquefaction system 1, similarly to the first modification of the sixth embodiment, the material gas is forwarded from the first compressor 4 to the second cooler 85 to be cooled therein via the line L20a, and is introduced into the first gas-liquid separation vessel 23 via the line L20b. However, in the fourth modification, the line L20b is directly connected to the first gas-liquid separation vessel 23 without the intervention of the liquefaction unit 21, and the material gas which forms the gas phase component in the first gas-liquid separation vessel 23 is forwarded to the piping system 30 positioned in the warm region Z1 or the warmest part of the liquefaction unit 21. Owing to this structure, in the fourth modification, the material gas that is introduced into the first gas-liquid separation vessel 23 is not required to be cooled (by introducing into the piping system 22), as opposed to the first modification so that the load on the liquefaction process of the liquefaction unit 21 can be reduced.

TABLE 12

	No.				
	(i)	(ii)	(iii)	(iv)	(v)
vapor phase fraction	1.00	0.99	1.00	0.00	1.00
temperature [C.]	20.0	4.2	-22.3	80.0	-6.4
pressure [kPa]	7500	5660	5500	5510	6814
molar flow rate [kgmole/h]	42000	42000	41420	1728	41420
mass flow rate [kg②]	807998	807998	757232	83213	757232
molar fraction					
nitrogen	0.007000	0.007000	0.007152	0.000007	0.007152
methane	0.871400	0.871400	0.893213	0.151770	0.893213
ethane	0.060900	0.060900	0.059298	0.149029	0.059298
propane	0.033600	0.033600	0.028208	0.241401	0.028208
butane	0.006500	0.006500	0.004279	0.081324	0.004279
n-butane	0.011500	0.011500	0.006458	0.172432	0.006458

TABLE 12-continued

i-pentane	0.003400	0.003400	0.000989	0.069908	0.000989
n-pentane	0.002100	0.002100	0.000385	0.046710	0.000385
n-hexane	0.003100	0.003100	0.000015	0.075276	0.000015
benzene	0.000500	0.000500	0.000002	0.012142	0.000002
toluene	0.000000	0.000000	0.000000	0.000000	0.000000
p-xylene	0.000000	0.000000	0.000000	0.000000	0.000000
n-heptane	0.000000	0.000000	0.000000	0.000000	0.000000
n-octane	0.000000	0.000000	0.000000	0.000000	0.000000

	No.			
	(vi)	(vii)	(viii)	(ix)
vapor phase fraction	0.97	0.00	1.00	0.00
temperature [C.]	-34.5	-34.5	-34.5	-160.9
pressure [kPa]	6749	6749	6749	120
molar flow rate	41420	1146	40274	40274
[kgmole/h]				
mass flow rate [kg②]	757232	32372	724861	724861
molar fraction				
nitrogen	0.007152	0.001979	0.007300	0.007300
methane	0.893213	0.575496	0.902252	0.902252
ethane	0.059298	0.135734	0.057123	0.057123
propane	0.028208	0.151884	0.024689	0.024689
butane	0.004279	0.039011	0.003291	0.003291
n-butane	0.006458	0.071862	0.004598	0.004598
i-pentane	0.000989	0.016367	0.000552	0.000552
n-pentane	0.000385	0.007216	0.000191	0.000191
n-hexane	0.000015	0.000396	0.000005	0.000005
benzene	0.000002	0.000056	0.000001	0.000001
toluene	0.000000	0.000000	0.000000	0.000000
p-xylene	0.000000	0.000000	0.000000	0.000000
n-heptane	0.000000	0.000000	0.000000	0.000000
n-octane	0.000000	0.000000	0.000000	0.000000

② indicates text missing or illegible when filed

Seventh Embodiment

[0180] FIG. 21 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a seventh embodiment of the present invention. In the liquefaction system illustrated in FIG. 21, the parts corresponding to those of the liquefaction system 1 of the first to sixth embodiments are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0181] The liquefaction system 1 of the seventh embodiment is similar to that of the sixth embodiment, but differs therefrom in that two expanders (first expander 3a and second expander 3b) are connected to the downstream end of the water removal unit 2 in parallel to each other. In the seventh embodiment, the first expander 3a and the second expander 3b are connected to a pair of compressors (first compressor 4a and third compressor 4b), respective, via a common shafts 5a, 5b in each case.

[0182] As shown in FIG. 21, the material gas expelled from the water removal unit 2 is forwarded to the first and second expanders 3a and 3b via respective lines L2a and L2b. The material gas expelled from the first and second expanders 3a and 3b is forwarded to the cooler 12 via lines L3a, L3b and L3. In this case, because the required cooling capacity of the cooling unit can be reduced, only a single cooler 12 using a low pressure (LP) propane refrigerant (C3R) is provided.

[0183] The material gas separated as a top fraction of the distillation unit 15 is forwarded to the third compressor 4b via a line L19 to be compressed. The material gas is then forwarded from the third compressor 4b to a piping system

22 positioned in the warm region Z1 to be cooled therein via the line L20, and is then introduced into the first gas-liquid separation vessel 23 via a line L21.

[0184] The first gas-liquid separation vessel 23 separates the liquid phase component (condensate) of the material gas, and the liquid phase component which is formed by hydrocarbons in liquid form is recirculated to the distillation unit 15 via an expansion valve 89 provided in a line L22. Meanwhile, the material gas that forms the gas phase component separated in the first gas-liquid separation vessel 23 is forwarded to the first compressor 4a via a line L24 to be compressed, and the material gas expelled from the first compressor 4a is introduced into a piping system 30 positioned in the warm region Z1 of the liquefaction unit 21 via a line L25.

[0185] According to the arrangement of the seventh embodiment using a pair of expanders 3a and 3b and a pair of compressors 4a and 4b, even when the material gas supplied to the liquefaction system 1 has a relatively high pressure and has a low critical pressure, the material gas can be compressed in an appropriate manner (without causing the material gas that is introduced into the distillation unit 15 to be compressed beyond the critical pressure) by using a plurality of compressors 4a and 4b.

Eighth Embodiment

[0186] FIG. 22 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as an eighth embodiment of the present invention. In the liquefaction system illustrated in FIG. 22, the parts corresponding to those of the liquefaction system 1 of the first to

seventh embodiments are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0187] The liquefaction system 1 of the eighth embodiment is similar to that of the sixth or the seventh embodiment, but differs therefrom in that the two first expanders 3a and 3b are connected in series, and a separator 91 is positioned between the two first expanders 3a and 3b.

[0188] As shown in FIG. 22, the material gas expelled from the water removal unit 2 is forwarded to the first expander 3a via a line L2 to be expanded therein, and is introduced into the separator 91 via a line L3. The material gas that is separated as a gas phase component in the separator 91 is forwarded to the second expander 3b via a line L26 to be expanded therein, and is forwarded to a cooler 12 via a line L27. Meanwhile, the liquid phase component (condensate) of the material gas is forwarded to the cooler 12 via an expansion valve 92 provided in a line L28.

[0189] According to the eighth embodiment, similarly to the seventh embodiment discussed above, even when the material gas supplied to the liquefaction system has a relatively high pressure and has a low critical pressure, the material gas can be compressed in an appropriate manner by using a plurality of compressors 4a and 4b.

First and Second Modifications of the Eighth Embodiment

[0190] FIGS. 23 and 24 are diagrams showing liquefaction process flows in systems for the liquefaction of natural gas given as a first and a second modification of the eighth embodiment of the present invention, respectively. In the liquefaction systems illustrated in FIGS. 23 and 24, the parts corresponding to those of the liquefaction system 1 of the eighth embodiment (including other embodiments and modifications) are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0191] As shown in FIG. 23, the liquefaction system 1 of the first modification is similar to the eighth embodiment, but differs therefrom in that the heat exchanger 69 is provided between the line L4 and the line L19. Therefore, the material gas separated as a top fraction in the distillation unit 15 and conducted through the line L19 is heated by exchanging heat with the material gas that flows through the line L4 leading from the cooler 12 to the distillation unit 15 before being introduced into the third compressor 4b. In the first modification, owing to this arrangement, even when the temperature of the material gas that is introduced into the liquefaction unit 21 via the line L20 should fall below an appropriate range, the temperature of the material gas can be raised appropriately by the exchange of heat in the heat exchanger 69.

[0192] As shown in FIG. 24, the liquefaction system 1 of the second modification is similar to the eighth embodiment, but differs therefrom in that the heat exchanger 69 is provided between the line L4 and the line L25. Therefore, the material gas compressed by the first compressor 4a and conducted through the line L25 is heated by exchanging heat with the material gas that flows through the line L4 leading from the cooler 12 to the distillation unit 15 before being introduced into the piping system 30 positioned in the warm region Z1 of the liquefaction unit 21. In the second modification, because the material gas that is heated in the heat exchanger 69 is directly introduced into the liquefaction unit

21 without the intervention of the first compressor 4, the temperature of the material gas that is introduced into the liquefaction unit can be controlled with ease.

[0193] The positioning of the heat exchanger 69 in the first and second modifications can be changed variously without departing from the spirit of the present invention as long as the temperature of the material gas that is to be introduced into the liquefaction unit 21 can be brought close to the temperature at the introduction point of the liquefaction unit 21.

Ninth Embodiment

[0194] FIG. 25 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a ninth embodiment of the present invention. In the liquefaction system illustrated in FIG. 25, the parts corresponding to those of the liquefaction system 1 of the first to eighth embodiments are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0195] The liquefaction system 1 of the ninth embodiment is advantageous in arrangements similar to the first modification of the sixth embodiment when the critical pressure of the material gas is relatively low and the pressure of the material gas expelled from the first compressor 4 to the first gas-liquid separation vessel 23 may be higher than the critical pressure (or when the first gas-liquid separation vessel 23 is unable to function properly). In this liquefaction system 1, the material gas is forwarded from a first compressor 4 to a second cooler 85 via a line L20a to be cooled therein, and is then forwarded to a piping system 22 positioned in the warm region Z1 of the liquefaction unit 21 via a line L20b to be further cooled therein. The material gas conducted through the line L21 is forwarded to lines L22 and L23 which branch out from a branch point of the line L21 one above the other so that a part of the material gas is recirculated to the distillation unit 15 via an expansion valve 89 provided in the lower line L22, and the remaining part of the material gas is introduced into the piping system 31 positioned in the intermediate region Z2 of the liquefaction unit 21 via the upper line L23. Owing to this arrangement, the liquefaction system 1 of the ninth embodiment allows the load on the liquefaction process in the liquefaction unit 21 to be reduced.

Modification of the Ninth Embodiment

[0196] FIG. 26 is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a modification of the ninth embodiment of the present invention. In the liquefaction system illustrated in FIG. 26, the parts corresponding to those of the liquefaction system 1 of the ninth embodiment are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0197] The liquefaction system 1 of this modification includes a second gas-liquid separation vessel 25 into which the material gas conducted through the line L22 is introduced via an expansion valve 89. The second gas-liquid separation vessel 25 separates the liquid phase component of the material gas, and recirculates the separated liquid phase component to the distillation unit 15 via an expansion valve 90 provided in a line L30. Meanwhile, the material gas that forms the gas phase component in the second gas-liquid

separation vessel **25** is forwarded to a line **L31** which is connected to a line **L19** so that the material gas is forwarded to the first compressor **4** via an expansion valve **93** provided in the line **L31**. Owing to this arrangement, the liquefaction system **1** of this modification has the advantage of stabilizing the process in the distillation unit **15**.

Tenth Embodiment

[0198] FIG. **27** is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as a tenth embodiment of the present invention. In the liquefaction system illustrated in FIG. **27**, the parts corresponding to those of the liquefaction system **1** of the first to ninth embodiments are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0199] The liquefaction system **1** of the tenth embodiment is similar to the sixth embodiment shown in FIG. **16**, but is similar to the example for comparison shown in FIG. **3** as far as the upstream part of the distillation unit **15** is concerned. More specifically, in the liquefaction system **1** of the tenth embodiment, the expander **3** is positioned on the downstream side of the cooling unit (three coolers **10**, **11** and **12** in this case), and the material gas expelled from the cooler **12** is forwarded to the separator **13** via the line **L4a** to be separated into gas and liquid. The material gas that forms the gas phase component in the separator **13** is forwarded to the expander **3** via the line **L4b**, and after being expanded in the expander **3**, is forwarded to the distillation unit **15** via the line **L4c**. The material gas that forms the liquid phase component in the separator **13** is forwarded to the line **L4d** provide with an expansion valve **14**. After being expanded in the expansion valve **14**, the liquid phase component is forwarded to the distillation unit **15** via the line **L4c** along with the material gas from the expander **3**.

[0200] In the liquefaction system **1** of the tenth embodiment, owing to this arrangement, by positioning the expander **3** on the downstream side of the cooling unit so as to reduce the output power thereof, the excessive rise in the temperature of the material gas that is compressed by the compressor **4** using the power provided by the expander **3** can be avoided so that the temperature of the material gas can be easily brought close to the temperature at the introduction point of the liquefaction unit **21** with ease. The advantage gained by the sixth embodiment can also be gained without regard to the arrangement of the first expander **3** and the coolers **11** and **12** (the cooler **10** is omitted in the sixth embodiment). In the liquefaction system **1** of the tenth embodiment, similarly as in the embodiment discussed in conjunction with the embodiment illustrated in FIG. **17**, a second cooler **85** using lower pressure propane as the refrigerant may be optionally provided on the downstream end of the first compressor **4**. Similarly as in the embodiment illustrated in FIG. **26**, instead of the first gas-liquid separation vessel **23**, a second gas-liquid separation vessel **25** may be provided in this liquefaction system **1** for receiving the material gas conducted through the line **L22** via an expansion valve **89**. In such a case, the structure surrounding the second gas-liquid separation vessel **25** (such as the lines **L30** and **L31**, and the expansion valves **89** and **90**) may be similar to that shown in FIG. **26**.

First and Second Modifications of the Tenth Embodiment

[0201] FIGS. **28** and **29** are diagrams showing liquefaction process flows in systems for the liquefaction of natural gas given as a first and a second modification of the tenth embodiment of the present invention, respectively. In the liquefaction systems illustrated in FIGS. **28** and **29**, the parts corresponding to those of the liquefaction system **1** of the tenth embodiment are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0202] As shown in FIG. **28**, the liquefaction system **1** of the first modification is similar to the tenth embodiment, but differs therefrom in that a heat exchanger **69** is provided between the line **L4a** and the line **L19** so that the material gas that is separated as a top fraction in the distillation unit **15** and conducted through the line **L19** is heated by exchanging heat with the material gas that flows through the line **L4a** from the cooler **12** to the separator **13**, on the upstream side of the first expander **3**, and is then introduced into the first compressor **4**. Owing to this arrangement, in the first modification, even when the temperature of the material gas that is introduced into the liquefaction unit **21** via the line **L20** should fall below an appropriate range, the temperature of the material gas can be maintained at an appropriate level by the exchange of heat in the heat exchanger **69**.

[0203] As shown in FIG. **29**, the liquefaction system **1** of the second modification is similar to the tenth embodiment, but differs therefrom in that the heat exchanger **69** is provided between the line **L4a** and the line **L25**. Therefore, the material gas compressed by the first compressor **4a** and conducted through the line **L20** is heated by exchanging heat with the material gas that flows through the line **L4a** leading from the cooler **12** to the separator **13** before being introduced into the piping system **22** positioned in the warm region **Z1** of the liquefaction unit **21**. In the second modification, because the material gas that is heated in the heat exchanger **69** is directly introduced into the liquefaction unit **21** without the intervention of the first compressor **4**, the temperature of the material gas that is introduced into the liquefaction unit can be controlled with ease.

Eleventh Embodiment

[0204] FIG. **30** is a diagram showing a liquefaction process flow in a system for the liquefaction of natural gas given as an eleventh embodiment of the present invention. In the liquefaction system illustrated in FIG. **30**, the parts corresponding to those of the liquefaction system **1** of the first to tenth embodiments are denoted with like numerals and omitted from the following discussion except for the matters that will be discussed in the following.

[0205] The liquefaction system **1** of the eleventh embodiment is similar to the sixth embodiment discussed above, but differs therefrom in that the first expander **3** is connected to the first compressor **4** similarly as in the fifth embodiment illustrated in FIG. **15**. More specifically, in the liquefaction system **1** of the eleventh embodiment, the first expander **3** and the first compressor **4** are not mechanically connected to each other, but are electrically connected to each other. The first expander **3** is connected to an electric generator **87**, and the power generated by the first expander **3** is converted into electric power by this electric generator **87**. The electric power generated by the electric generator **87** is supplied to

an electric motor **84** that drives the first compressor **4**. In other words, the power generated by the first expander **3** is used by the first compressor **4**. The electric power supplied by the electric generator **87** may be at least a part of the electric power that is used for driving the electric motor **84**, and when there is a shortage of electric power, the external power source may be used for augmenting the shortfall of the electric power.

(Modifications of the Expander and the Compressor)

[0206] FIGS. **31** and **32** are diagram showing a first and a second variation of the mechanical connecting arrangement between the expander and the compressor in the system for the liquefaction of natural gas that may be use in the various embodiments discussed above.

[0207] In the variation illustrated in FIG. **31**, an electric motor (second electric motor) **84** is interposed between the first expander **3** and the first compressor **4**, and the speed of the electric motor **84** is controlled by a controller **82** for variable frequency control drive. The electric motor **84** receives a supply of electric power from an external source. The first expander **3**, the first compressor **4** and the electric motor **84** are provided on a common shaft, and the power generated by the first expander **3** by the expansion of the material gas can be used for driving the first compressor **4**. Thereby, the power requirement of the electric motor **84** can be reduced. By thus using the power of the electric motor **84** for augmenting the power generated by the first expander **3**, the outlet pressure of the first compressor **4** can be increased in a stable manner.

[0208] In the variation illustrated in FIG. **32**, the shafts of the first expander **3**, the first compressor **4** and the electric motor **84** are fitted with gears **96**, **97** and **98**, respectively. The gear **96** of the first expander **3** meshes with the gear **97** of the electric motor **84**, and the gear **97** of the electric motor **84** meshes with the gear **98** of the first compressor **4**. Thus, the first expander **3** and the first compressor **4** are connected in a power transmitting relationship (connected mechanically) via the electric motor **84**. Owing to this arrangement, by using the power of the electric motor **84** to augment the power generated by the first expander **3**, the outlet pressure of the first compressor **4** can be increased in a stable manner. The connecting arrangement between the first expander **3**, the first compressor **4** and the electric motor **84** may consist of any per se known gear mechanisms such as a planetary gear mechanism.

[0209] The present invention has been described in terms of specific embodiments, but these embodiments are only examples, and do not limit the present invention in any way. The various components of the liquefaction systems and the liquefaction methods for the liquefaction of the natural gas according to the present invention are not necessarily entirely indispensable, but may be suitably substituted and omitted without departing from the spirit of the present invention.

GLOSSARY

[0210] **1** liquefaction system
 [0211] **2** water removal unit
 [0212] **3, 3a** first expander
 [0213] **3b** second expander
 [0214] **4, 4a** first compressor
 [0215] **4b** third compressor

[0216] **5** shaft
 [0217] **10, 11, 12** first cooler
 [0218] **15** distillation unit
 [0219] **21** liquefaction unit
 [0220] **23** first gas-liquid separation vessel
 [0221] **33** expansion valve
 [0222] **41** refrigerant separator
 [0223] **44** expansion valve
 [0224] **45** spray header
 [0225] **54** expansion valve
 [0226] **55** spray header
 [0227] **69** heat exchanger
 [0228] **71** fourth compressor
 [0229] **72** fourth cooler
 [0230] **75** second compressor
 [0231] **81** electric motor (first electric motor)
 [0232] **82** controller
 [0233] **83** pressure gauge
 [0234] **84** electric motor (second electric motor)
 [0235] **85** second cooler
 [0236] **86** third cooler
 [0237] **87** electric generator
 [0238] **89** expansion valve
 [0239] **91** separator
 [0240] **92** expansion valve
 [0241] **96, 97, 98** gear
 [0242] **Z1** warm region
 [0243] **Z2** intermediate region
 [0244] **Z3** cold region

1. A system for the liquefaction of natural gas that cools the natural gas to produce liquefied natural gas, comprising:

- a first expander for generating power by expanding natural gas under pressure as material gas;
- a first cooling unit for cooling the material gas depressurized by expansion in the first expander;
- a distillation unit for reducing or eliminating a heavy component in the material gas by distilling the material gas cooled by the first cooling unit;
- a first compressor for compressing the material gas from which the heavy component was reduced or eliminated by the distillation unit by using the power generated in the first expander; and
- a liquefaction unit for liquefying the material gas compressed by the first compressor by exchanging heat with a refrigerant.

2. The system for the liquefaction of natural gas according to claim **1**, further comprising a second cooling unit placed between the first compressor and the liquefaction unit to cool the material gas compressed by the first compressor.

3. The system for the liquefaction of natural gas according to claim **1**, wherein the liquefaction unit comprises a spool-wound heat exchanger, and the material gas expelled from the first compressor is introduced into a warm region of the spool-wound heat exchanger located on a hot side of the spool-wound heat exchanger.

4. The system for the liquefaction of natural gas according to claim **1**, further comprising a second compressor placed between the first compressor and the liquefaction unit for compressing the material gas expelled from the first compressor.

5. The system for the liquefaction of natural gas according to claim **4**, further comprising a first electric motor powered by an external electric power and controlled in dependence

on a pressure value of the material gas introduced into the liquefaction unit, and the second compressor is driven by the first motor.

6. The system for the liquefaction of natural gas according to claim 4, further comprising a second cooling unit placed between the second compressor and the liquefaction unit to cool the material gas.

7. The system for the liquefaction of natural gas according to claim 1, further comprising an electric generator unit for converting the power generated by the first expander into electric power and a second electric motor for driving the first compressor, the second electric motor being powered by electric power generated by the generator unit.

8. The system for the liquefaction of natural gas according to claim 1, further comprising a second electric motor mechanically coupling the first expander and the first compressor to each other and powered by external electric power, wherein the first compressor is configured to compress the material gas by using the power generated by the first expander and power generated by the second electric motor.

9. The system for the liquefaction of natural gas according to claim 1,

wherein the material gas from which the heavy component is reduced or eliminated by the distillation unit is directly introduced into the first compressor, and the system further comprises a first gas-liquid separation vessel for receiving the material gas compressed by the first compressor via the liquefaction unit; and
wherein a gas phase component of the material gas separated in the first gas-liquid separation vessel is introduced into the liquefaction unit once again, and a liquid phase component of the material gas is recirculated to the distillation unit.

10. The system for the liquefaction of natural gas according to claim 9, further comprising a second cooling unit placed between the first compressor and the first gas-liquid separation vessel to cool the material gas.

11. The system for the liquefaction of natural gas according to claim 1, further comprising: a second expander placed between the first expander and the distillation unit to generate power by expanding the material gas; and

a third compressor placed between the distillation unit and the first compressor to compress the material gas distilled by the distillation unit by using the power generated by the second expander.

12. The system for the liquefaction of natural gas according to claim 1, further comprising:

a second expander placed in parallel with the first expander to generate power by expanding the material gas; and

a third compressor placed between the distillation unit and the first compressor to compress the material gas distilled by the distillation unit by using the power generated by the second expander.

13. The system for the liquefaction of natural gas according to claim 1, wherein the liquefaction unit comprises a plate-fin heat exchanger.

14. The system for the liquefaction of natural gas according to claim 1, wherein the material gas compressed by the first expander has a pressure higher than 5,171 kPaA.

15. The system for the liquefaction of natural gas according to claim 4, wherein the material gas compressed by the second expander has a pressure higher than 5,171 kPaA.

16. The system for the liquefaction of natural gas according to claim 1, further comprising a heat exchanger for exchanging heat between the material gas introduced into the distillation unit and a top fraction from the distillation unit.

17. The system for the liquefaction of natural gas according to claim 1, further comprising a first gas-liquid separation vessel for receiving a top fraction from the distillation unit, and a third cooling unit placed between the distillation unit and the first gas-liquid separation vessel to cool the top fraction from the distillation unit.

18. The system for the liquefaction of natural gas according to claim 1, further comprising a second heat exchanger for exchanging heat between the material gas to be introduced into the first compressor and the material gas compressed by the first compressor.

19. The system for the liquefaction of natural gas according to claim 18, further comprising a fifth cooling unit for cooling the material gas compressed by the first compressor at a point upstream of the second heat exchanger by using a water, air or propane refrigerant.

20. The system for the liquefaction of natural gas according to claim 18, further comprising a third heat exchanger for exchanging heat between the material gas compressed by the first compressor and the top fraction from the distillation unit.

21. A system for the liquefaction of natural gas that cools the natural gas to produce liquefied natural gas, comprising:

- a first expander for generating power by expanding natural gas under pressure as material gas;
- a distillation unit for reducing or eliminating a heavy component in the material gas by distilling the material gas depressurized by expansion in the first expander;
- a first compressor for compressing the material gas from which the heavy component was reduced or eliminated by the distillation unit by using power generated in the first expander; and
- a liquefaction unit for liquefying the material gas compressed by the first compressor by exchanging heat with a refrigerant.

22. A method for the liquefaction of natural gas by cooling the natural gas to produce liquefied natural gas, comprising:

- a first expansion step for generating power by expanding natural gas under pressure as material gas;
- a first cooling step for cooling the material gas depressurized by expansion in the first expansion step;
- a distillation step for reducing or eliminating a heavy component in the material gas by distilling the material gas cooled in the first cooling step;
- a first compression step for compressing the material gas from which the heavy component was reduced or eliminated in the distillation step by using the power generated in the first expansion step; and
- a liquefaction step for liquefying the material gas compressed in the first compression step by exchanging heat with a refrigerant.

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